Electron cloud at the LHC and LHC injectors

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Outline

- Basics of electron cloud in particle accelerators
  - Electron cloud build up and effects on the beam
  - Scrubbing
- Electron cloud studies in the CERN accelerators
- Closing remarks

Basics of electron cloud

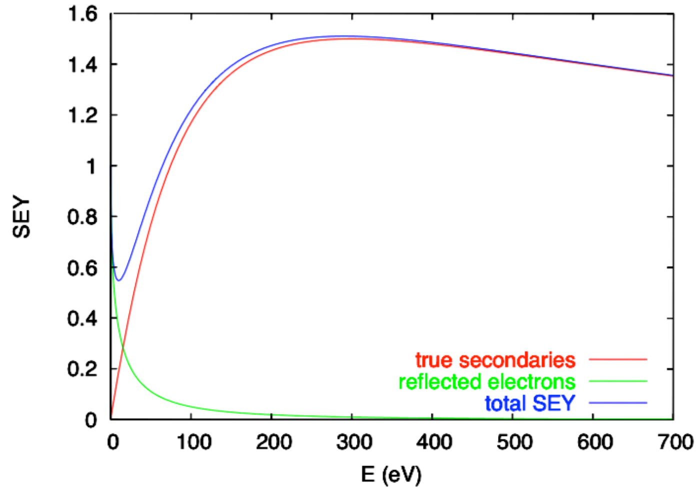
Generation of electrons inside the vacuum chamber (primary, or seed, electrons)

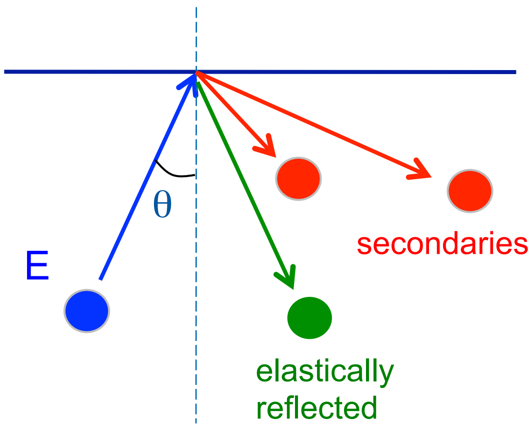
- **Residual gas ionization**
- **Photoelectrons from synchrotron radiation**
- **Desorption from the losses on the wall**

Basics of electron cloud

Generation of electrons inside the vacuum chamber
(primary, or seed, electrons)

- Acceleration of primary electrons in the beam field
- Secondary electron production when hitting the wall



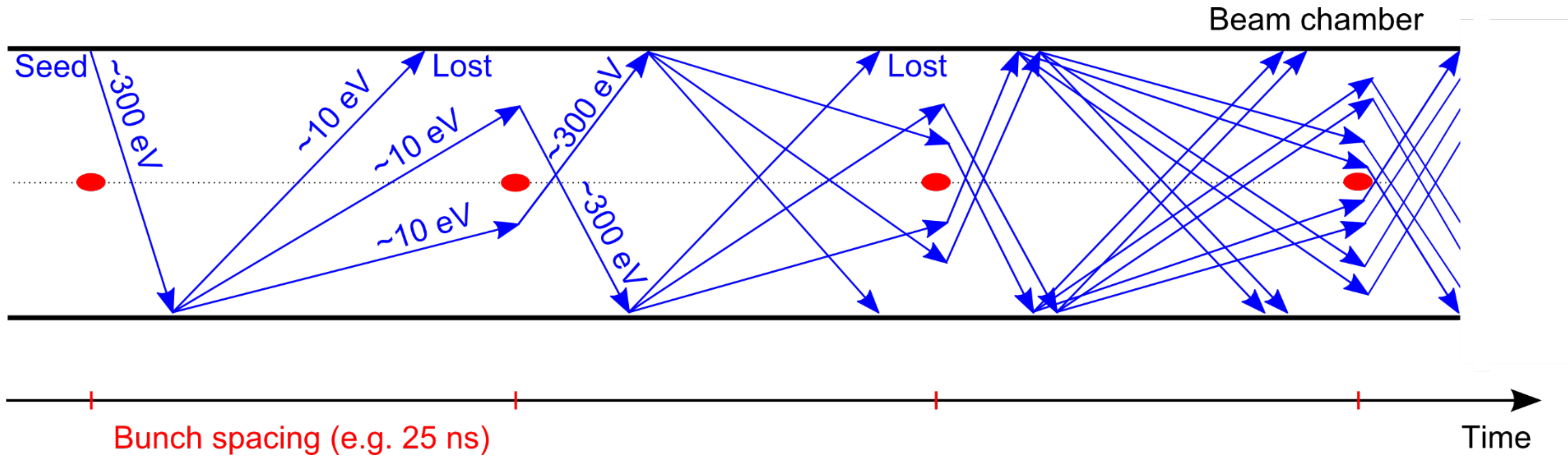


Dangerous if
SEY > 1

Basics of electron cloud

Generation of electrons inside the vacuum chamber
(primary, or seed, electrons)

- Acceleration of primary electrons in the beam field
- Secondary electron production when hitting the wall
- Avalanche electron multiplication



Basics of electron cloud

Generation of electrons inside the vacuum chamber
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↓

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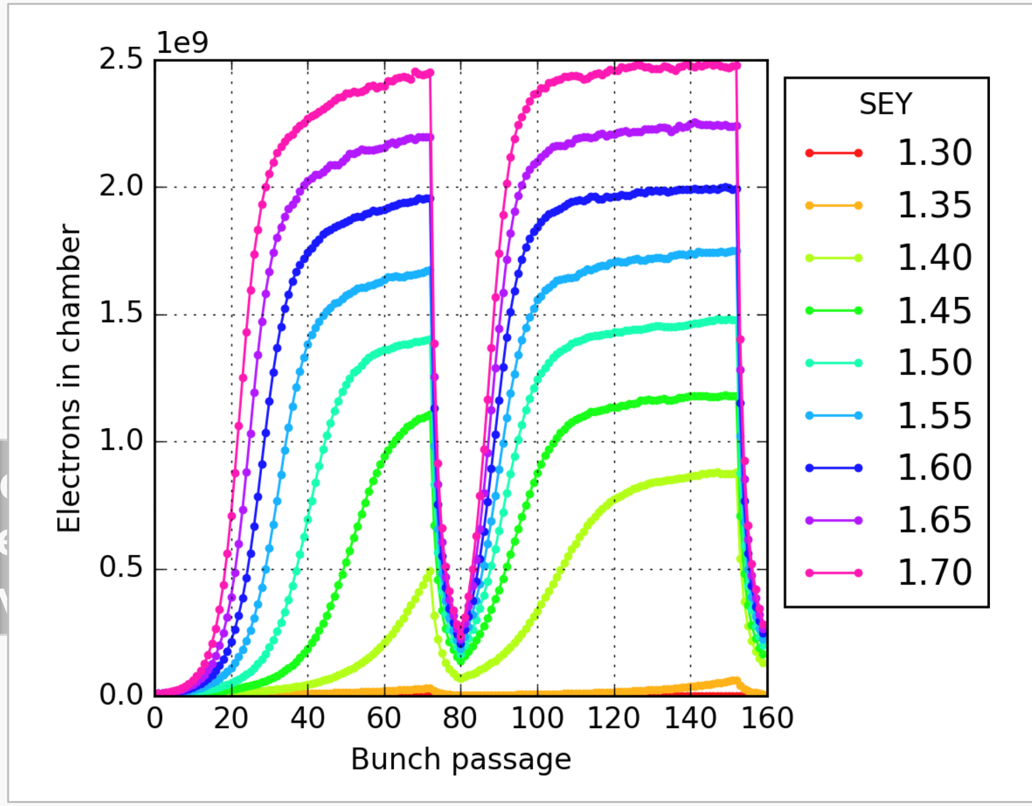
↓

After the passage of several bunches, the electron distribution inside the chamber reaches a dynamic steady state (electron cloud)

Basics of electron cloud

- Ac ... ield
- Se ... e wall
- Av



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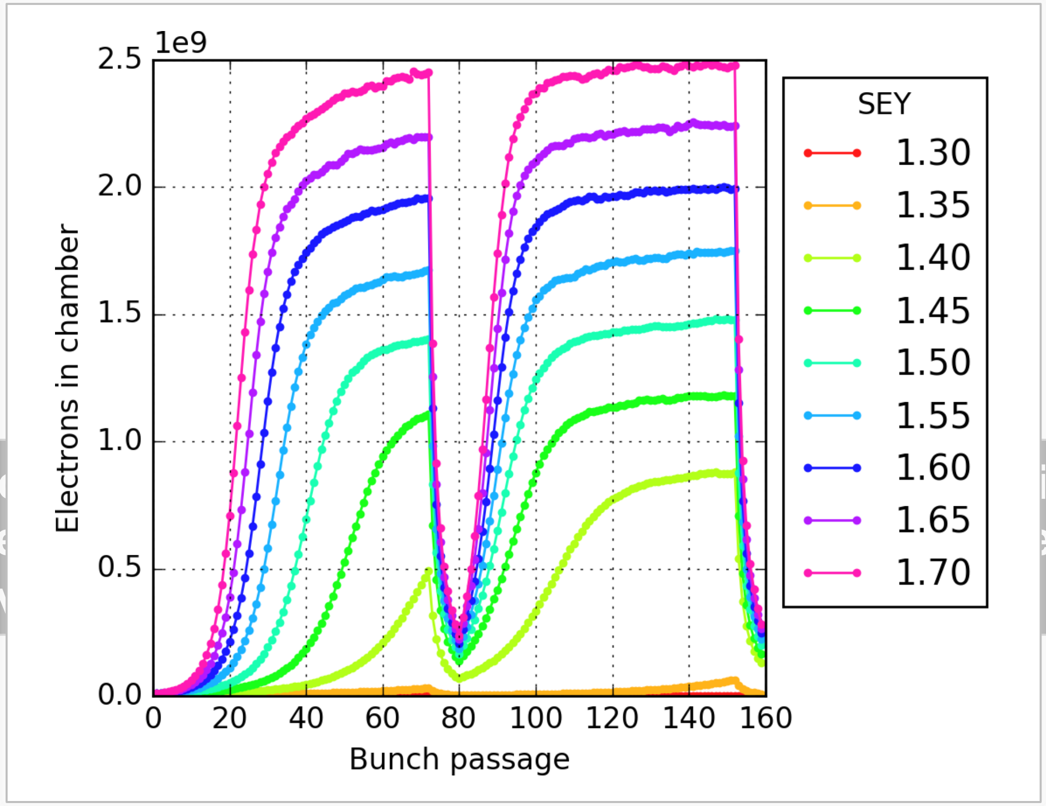
Basics of electron cloud



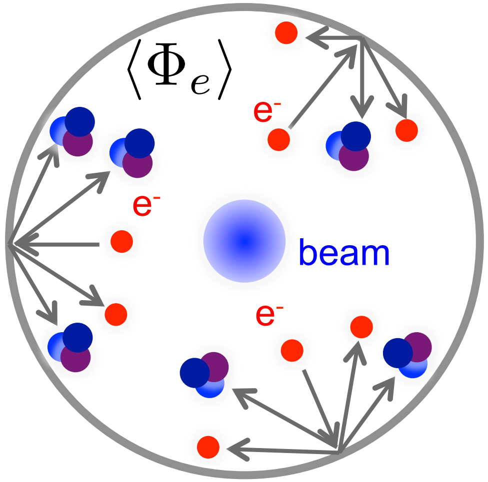
- Ac... ...ield
- Se... ...e wall
- Av...

After the passage of several bunches, the electron distribution inside the chamber reaches a dynamic steady state (electron cloud)
→ Several effects associated

Effects of the electron cloud

The presence of an e-cloud inside an accelerator ring is revealed by several **typical signatures**

- ✓ Fast pressure rise, outgassing
- ✓ Additional heat load
- ✓ Baseline shift of the pick-up electrode signal
- ✓ Synchronous phase shift due to the energy loss



$$\Delta P \propto \int \eta_e(E) \langle \Phi_e(E) \rangle dE$$

$$\Delta W = \int \langle \Phi_e(E) \rangle E dE$$

Effects of the electron cloud

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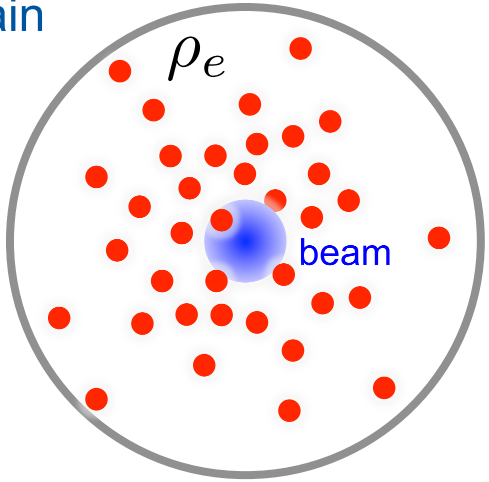
- ✓ Baseline shift of the pick-up electrode signal

} Machine observables

- ✓ Synchronous phase shift due to the energy loss
- ✓ Tune shift along the bunch train
- ✓ Coherent instability
  - Single bunch effect affecting the last bunches of a train
  - Coupled bunch effect
- ✓ Poor beam lifetime and emittance growth



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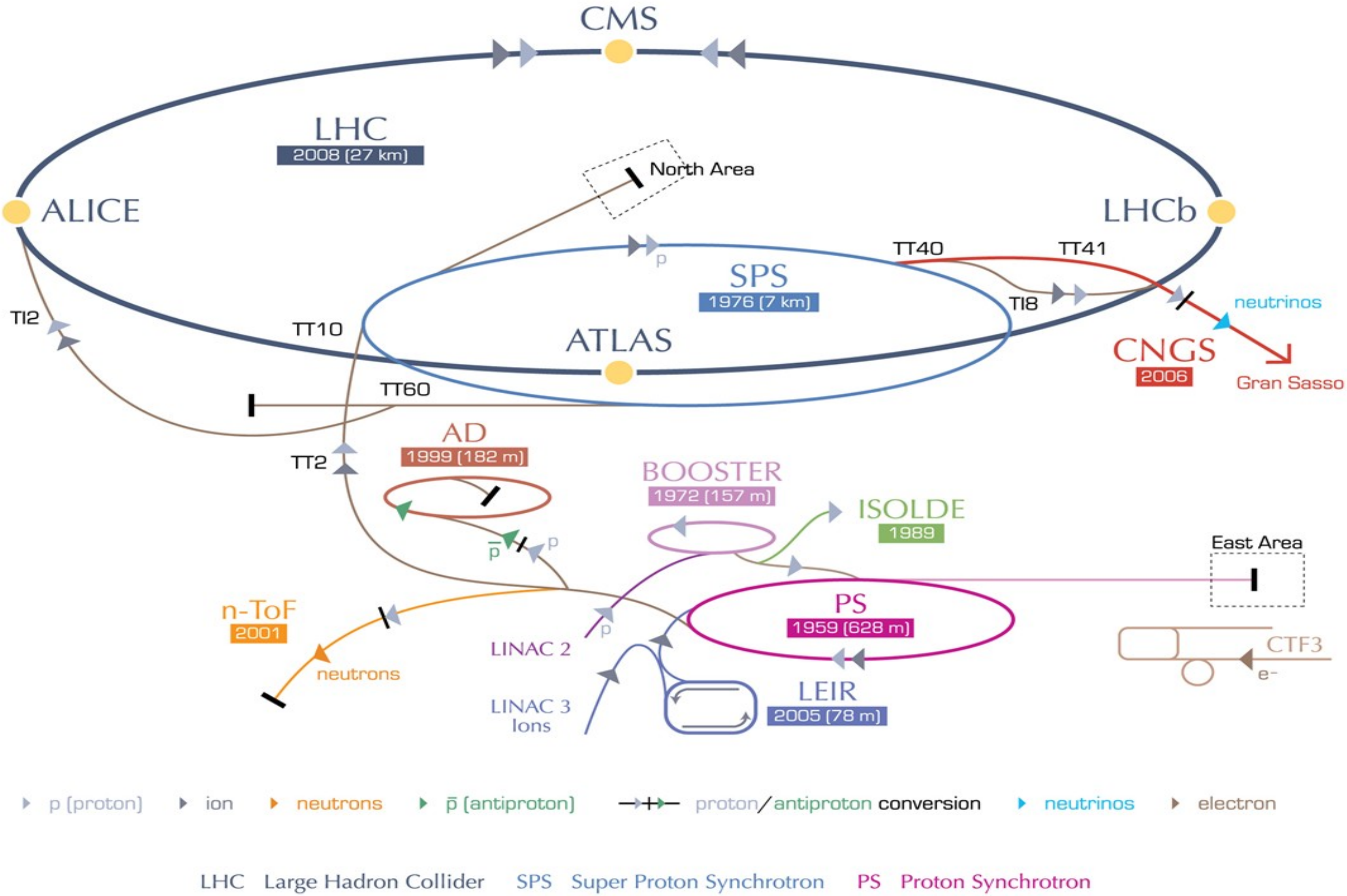
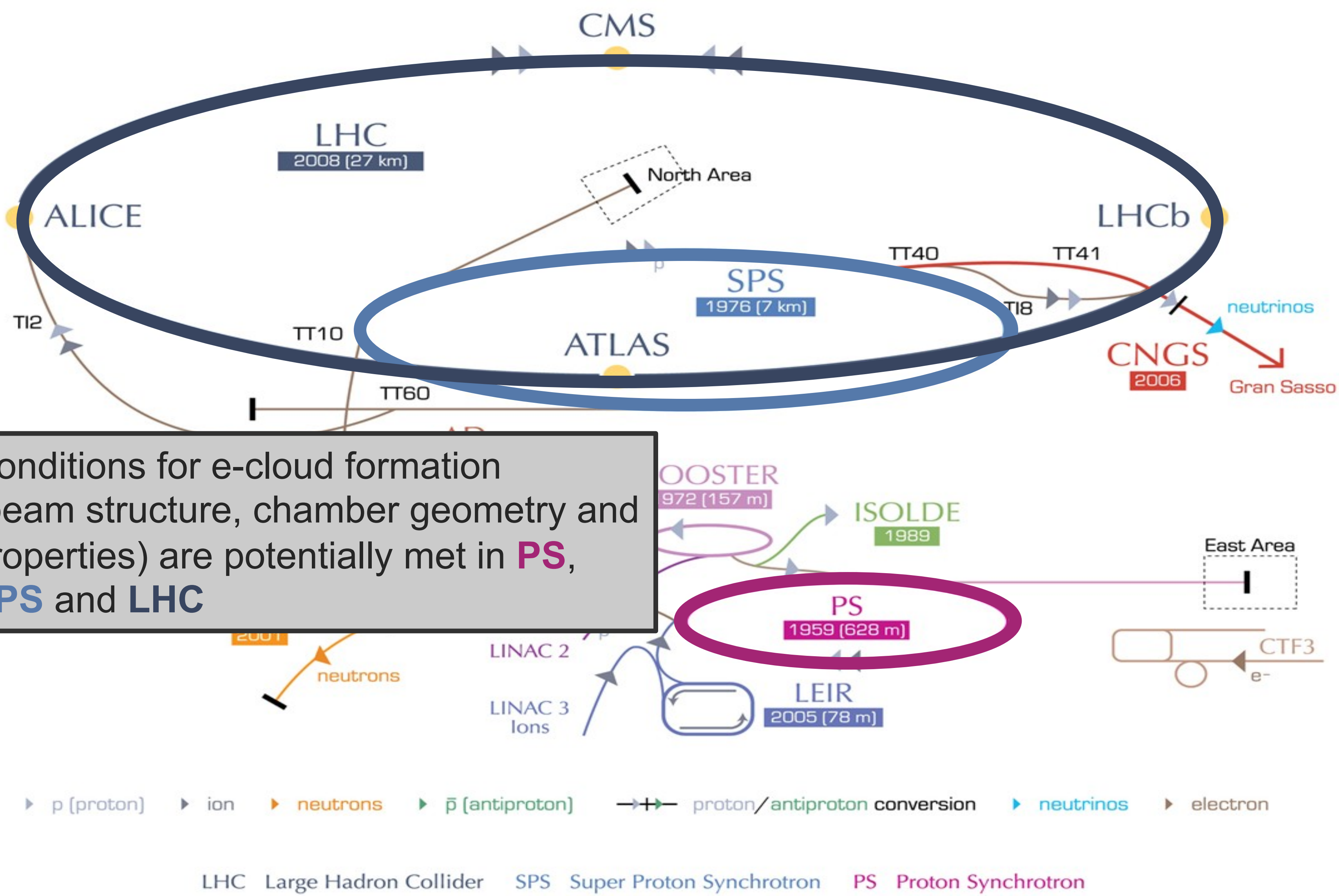
} Beam observables

- ✓ Active monitoring: signal on dedicated electron detectors (e.g. strip monitors) and retarding field analysers

CERN's accelerator complex



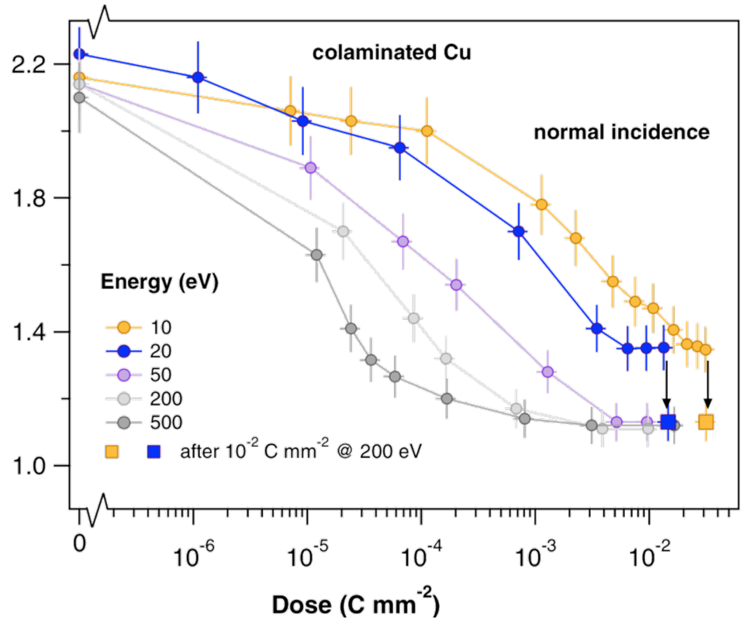
CERN's accelerator complex



Conditions for e-cloud formation (beam structure, chamber geometry and properties) are potentially met in **PS**, **SPS** and **LHC**

Surface scrubbing

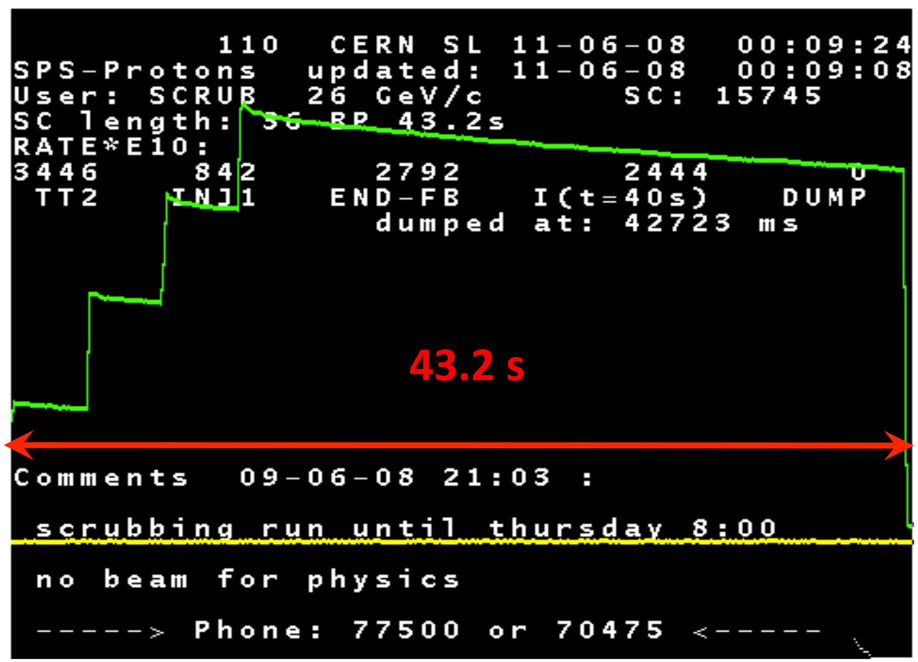
- Fortunately, the SEY of a surface becomes lower under electron bombardment (scrubbing)
- Laboratory measurements show that
  - SEY decreases quickly at the beginning of the process, then slows down
  - Electrons with different energies have different ‘scrubbing efficiency’
  - The ‘final’ value of SEY depends on material, e^- energy, temperature, vacuum composition, more?



R. Cimino *et al.*, **ECLOUD12**, Elba Island

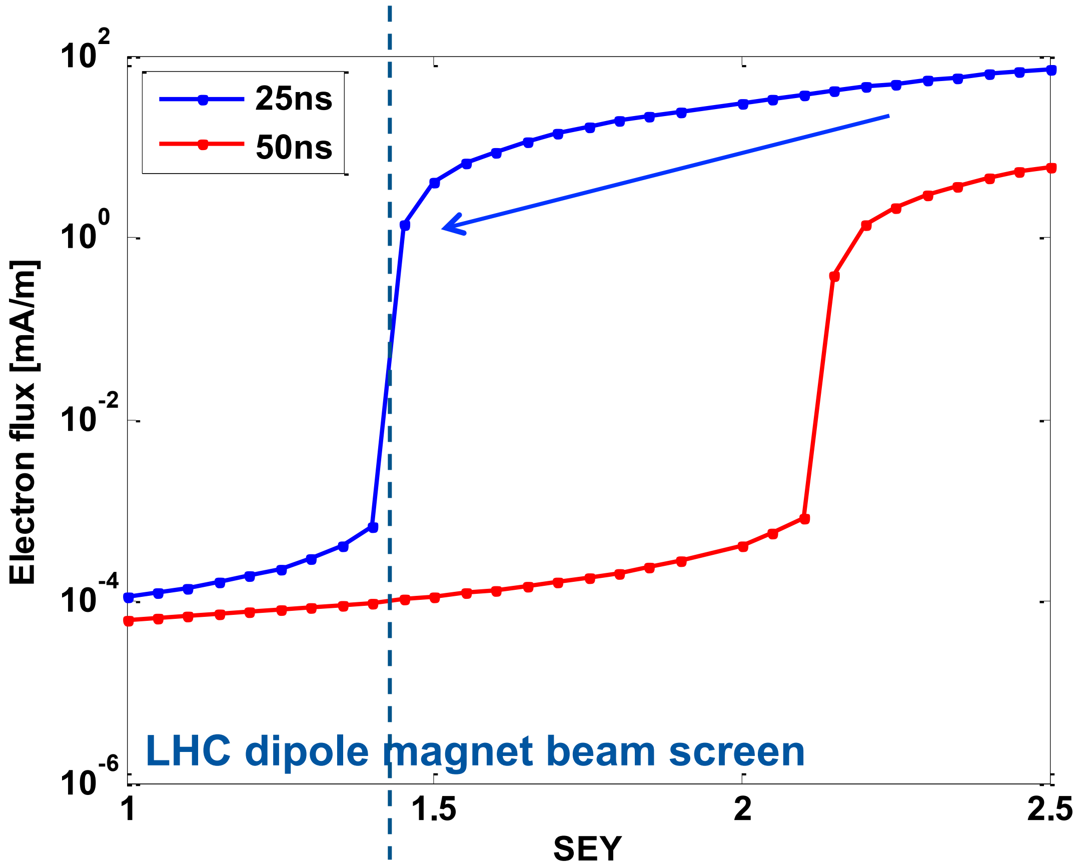
Surface scrubbing

- If the accelerator can be run in **e-cloud regime**, scrubbing is expected to naturally occur
  - Fortunately **beam dynamics knobs** exist to preserve beam stability, although lifetime might be poor in presence of significant e-cloud (which affects scrubbing efficiency)
  - Dedicated **scrubbing runs** can be used to lower the SEY



Surface scrubbing

- **Beam-induced scrubbing** is different from lab scrubbing
  - It becomes even slower while it progresses, due to the decrease of the electron flux as the SEY decreases



Surface scrubbing

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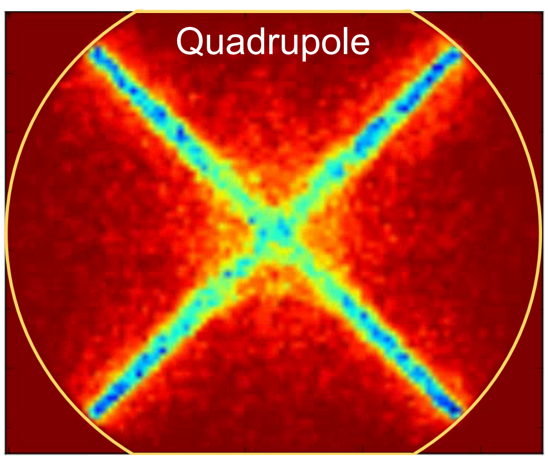
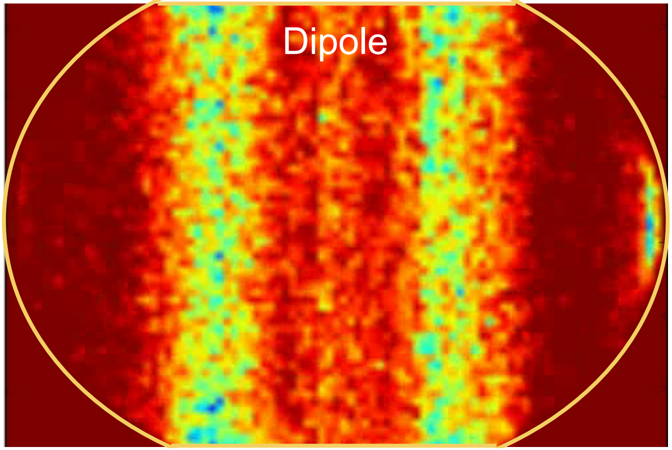
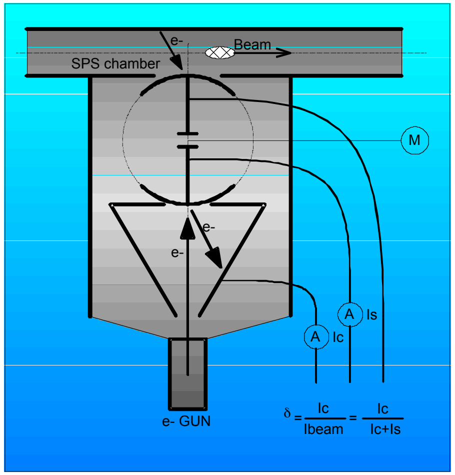
  - It comes from pulsed electron bombardment (MHz) with a broad spectrum of energies
  - It happens in the vacuum chamber of an accelerator
    - It is localized according to e-cloud distribution pattern and may be affected when beam properties or magnetic field change
    - It is affected by other mechanisms (ion or photon bombardment)
    - Its evolution is related to vacuum dynamics in the chamber



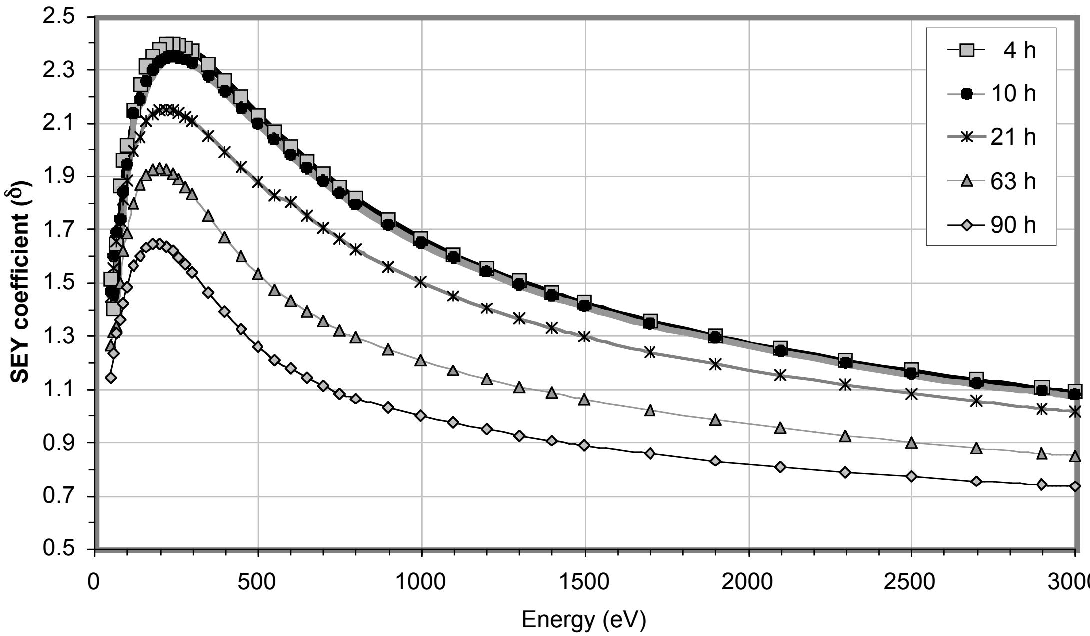


Surface scrubbing

- **Beam-induced scrubbing**
  - Has been measured directly at the SPS with StSt rotatable sample exposed to the beam or to SEY measurement device (2004)

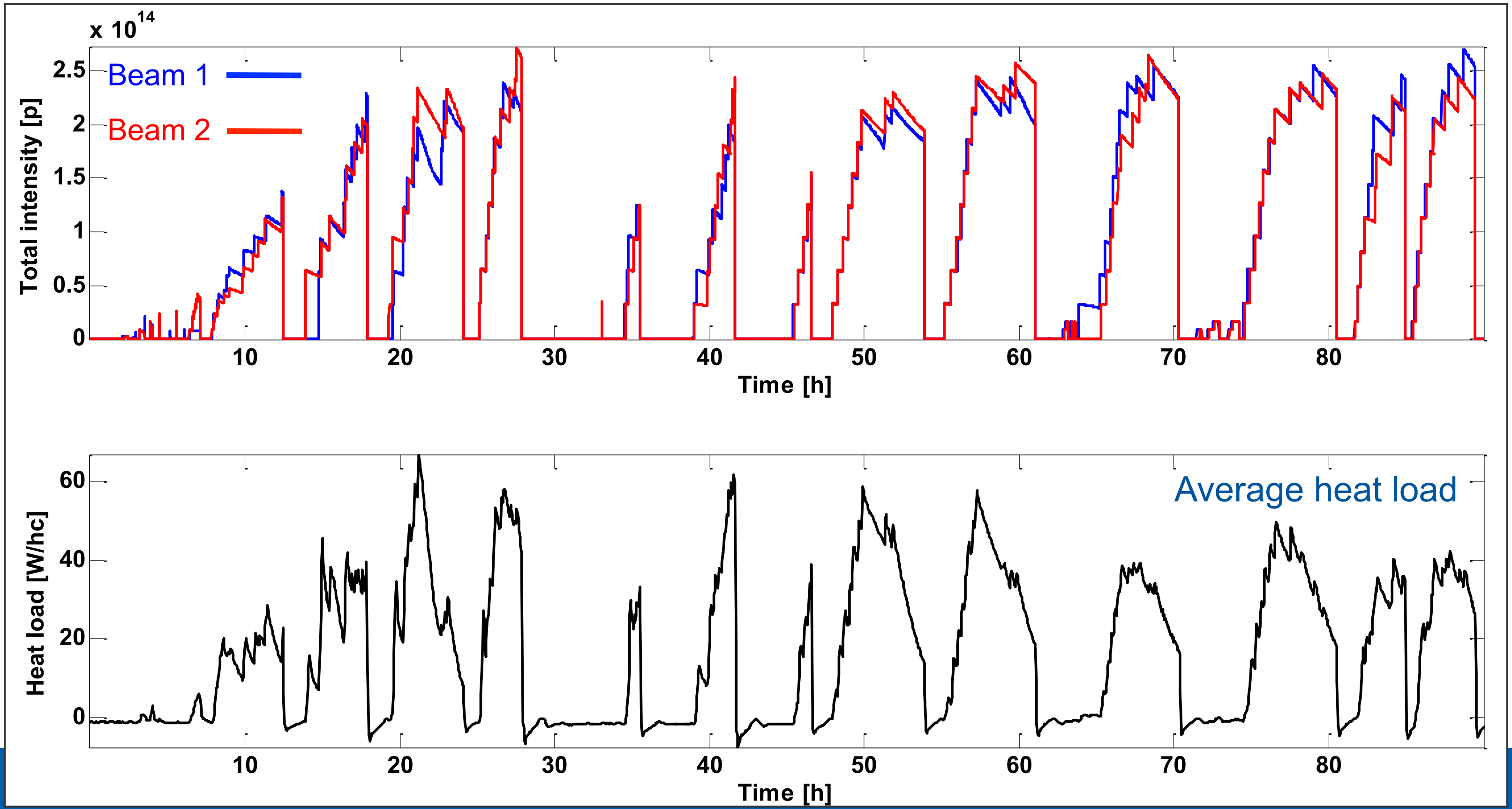


Schematic view of the in-situ SEY detector installed in the SPS



Surface scrubbing

- **Beam-induced scrubbing**
  - Is revealed by improving accelerator conditions over time, e.g. decrease of pressure rise, heat load, stable phase shift, improvement of beam quality → not obvious sometimes, as timescales can be long and effects are entangled



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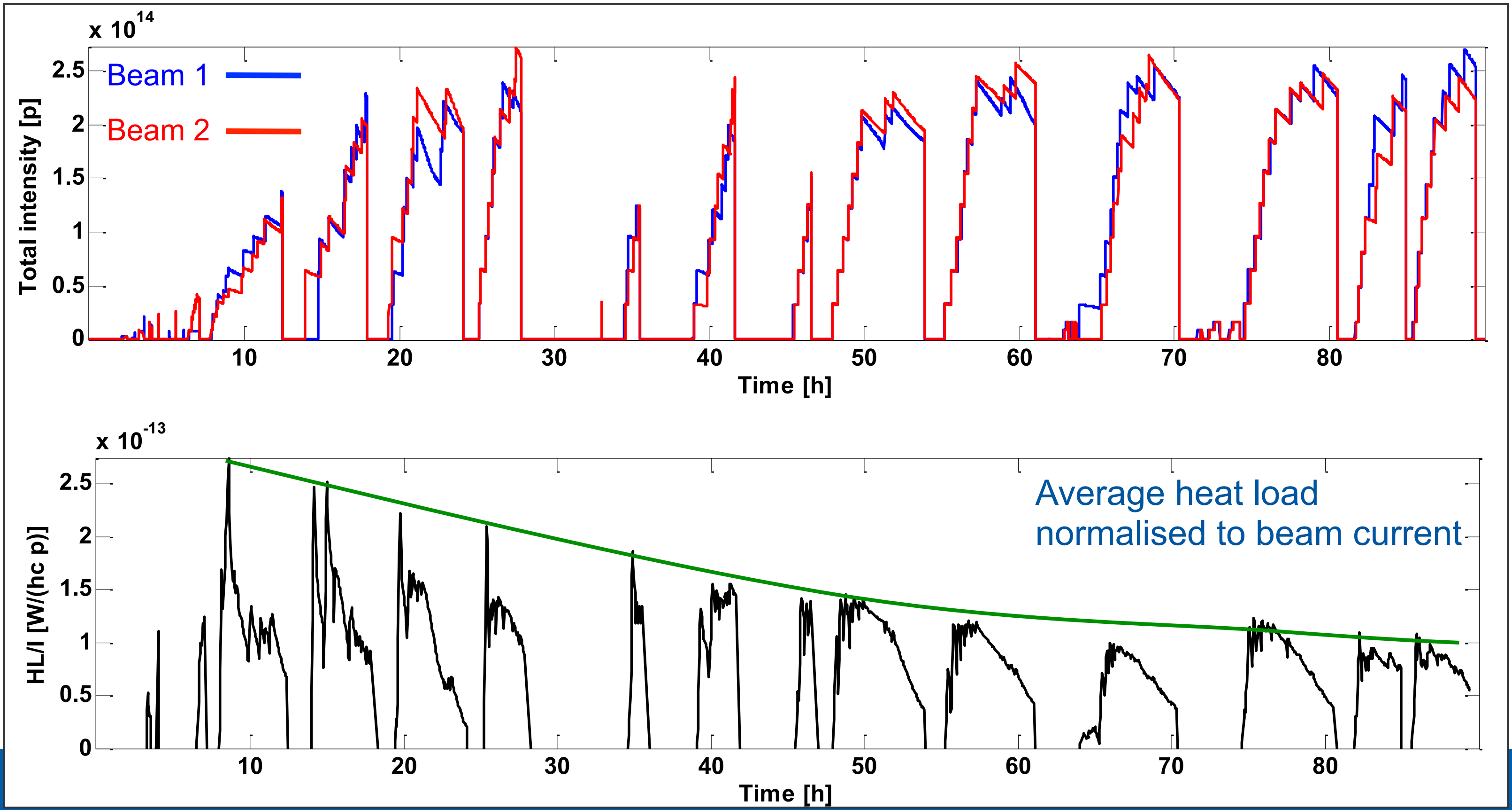
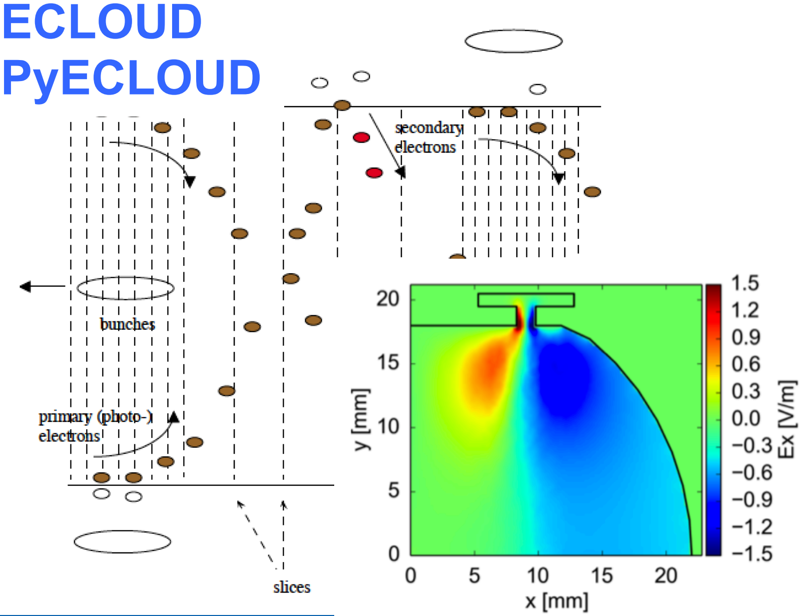


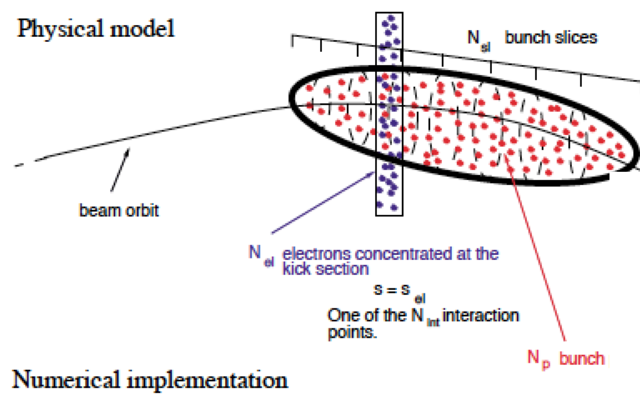
Electron cloud in the CERN accelerators

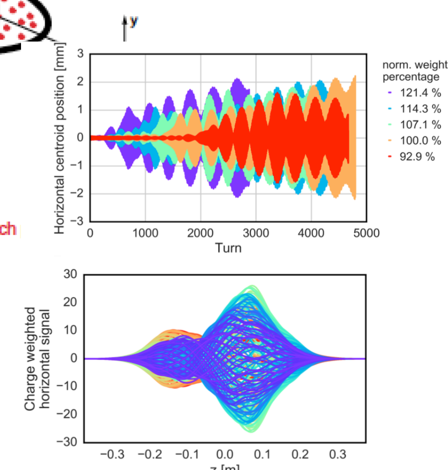
- The e-cloud has been observed/studied at the
  - **Proton Synchrotron (PS)**
  - **Super Proton Synchrotron (SPS)**
  - **Large Hadron Collider (LHC)**

ECLOUD
PyECLOUD



HEADTAIL
PyHEADTAIL





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THPAB043

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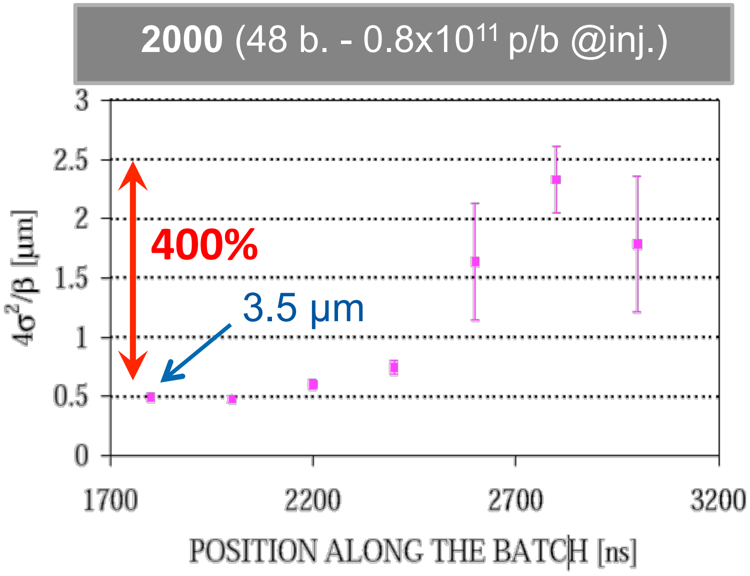
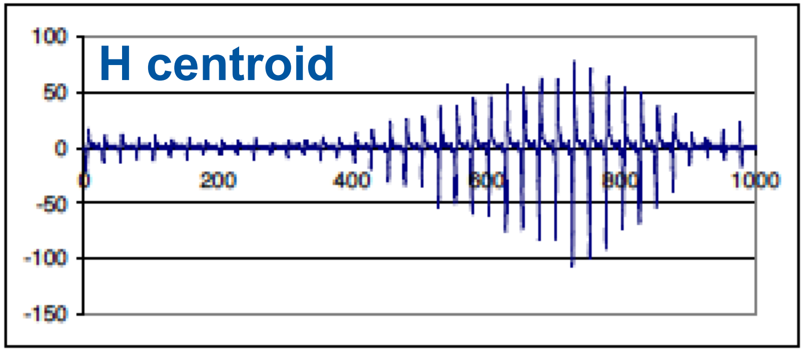
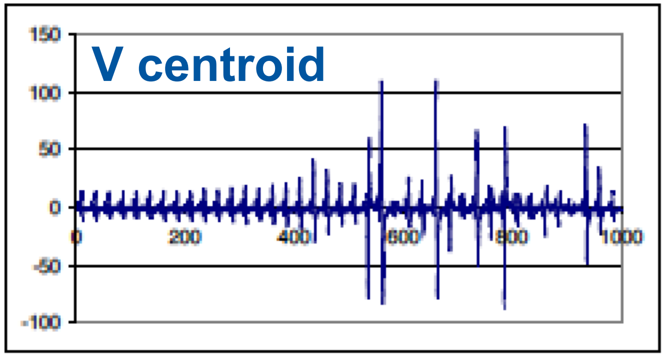
… some highlights for SPS and LHC …

Electron cloud in the SPS

- Strong limitation due to e-cloud with 25 ns beams until ~2011
  - Instabilities at injection to be cured with high chromaticity (V) and transverse feedback system (H)
  - Severe pressure rise around the machine
  - Strong emittance growth along bunch trains







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  - Instabilities at injection to be cured with high chromaticity (V) and transverse feedback system (H)
  - Severe pressure rise around the machine
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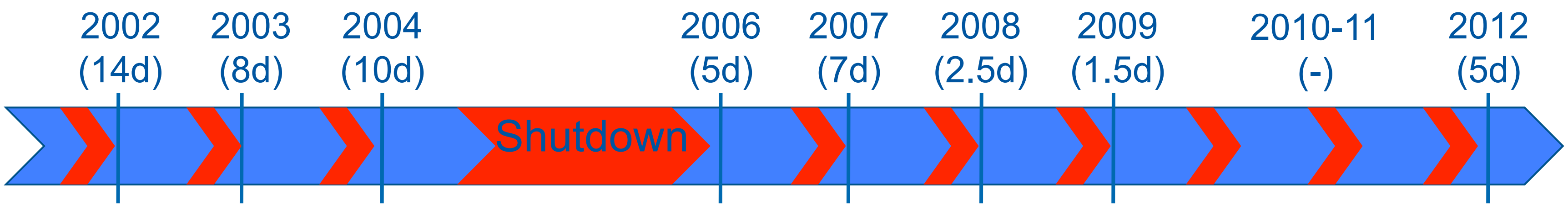
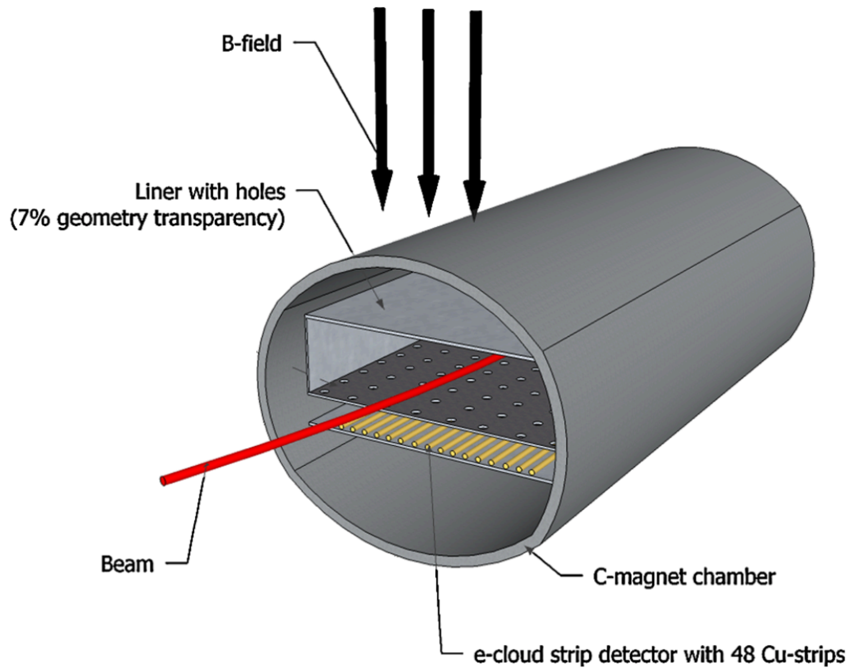
- **Scrubbing runs** since 2002 with long cycles at 26 GeV (each lasting from 2 days to 2 weeks)
- No significant degradation seen for **four trains of 72 bunches of nominal 25 ns beam (1.2e11 p/b)** after 2010



~1 month before 2005 long shutdown
16 days in 2006 – 2009

Electron cloud in the SPS

- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
  - Four monitors installed to measure e-cloud in different geometries, with different materials or surface treatment (with possible B field)
  - Reconstruction of **horizontal profile** but no time resolved signal

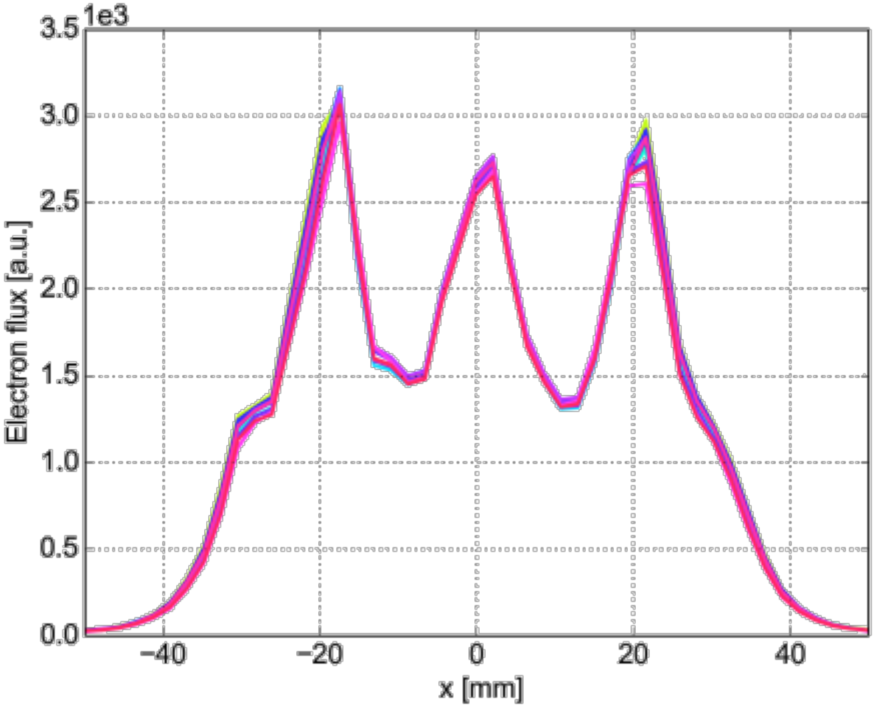


Electron cloud in the SPS

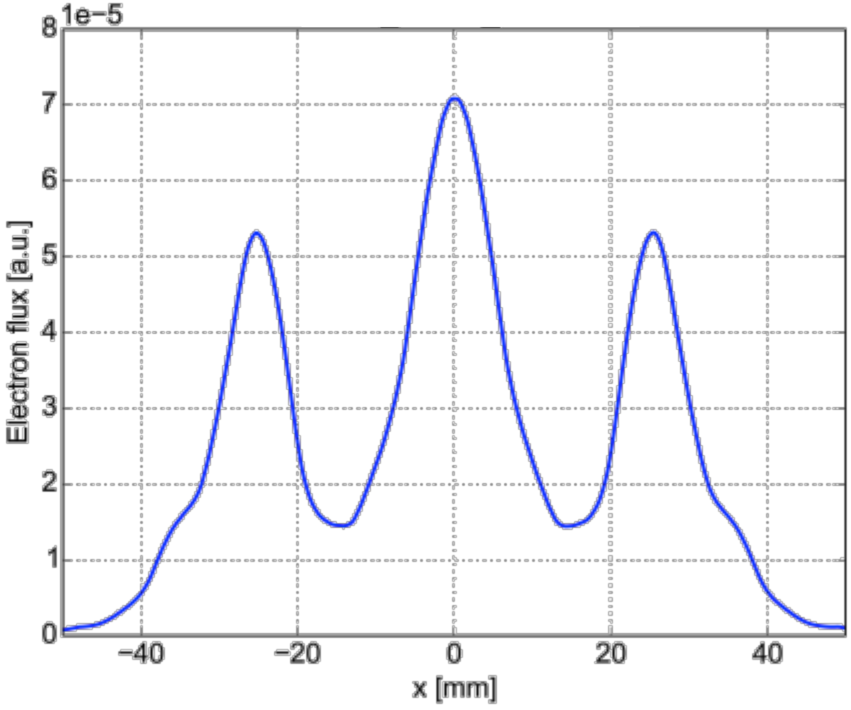
- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
  - Comparing experimental data against simulations for different magnetic fields applied

B = 42 G

Measurement



Simulation

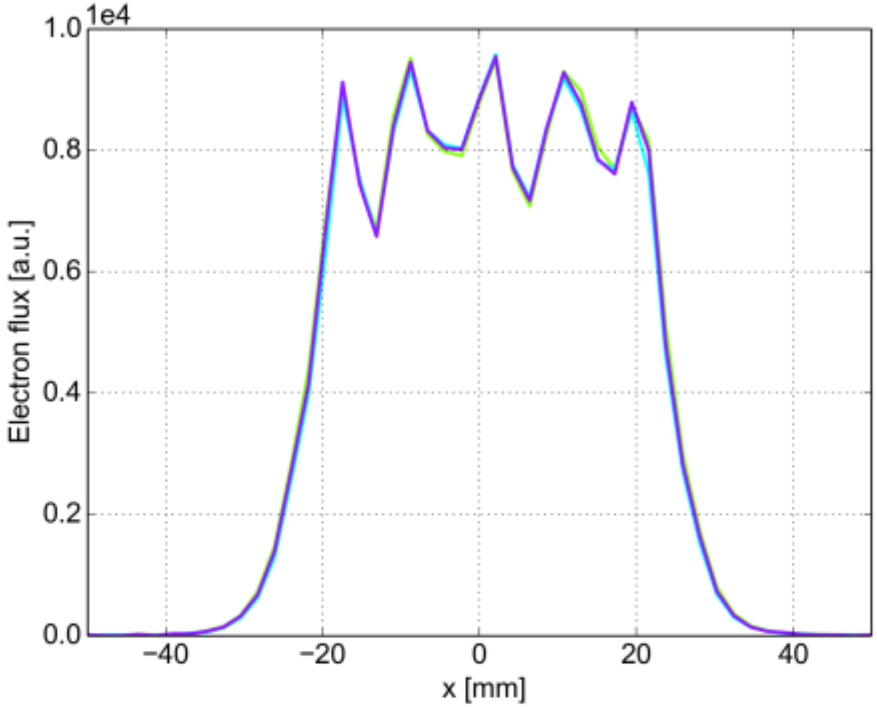


Electron cloud in the SPS

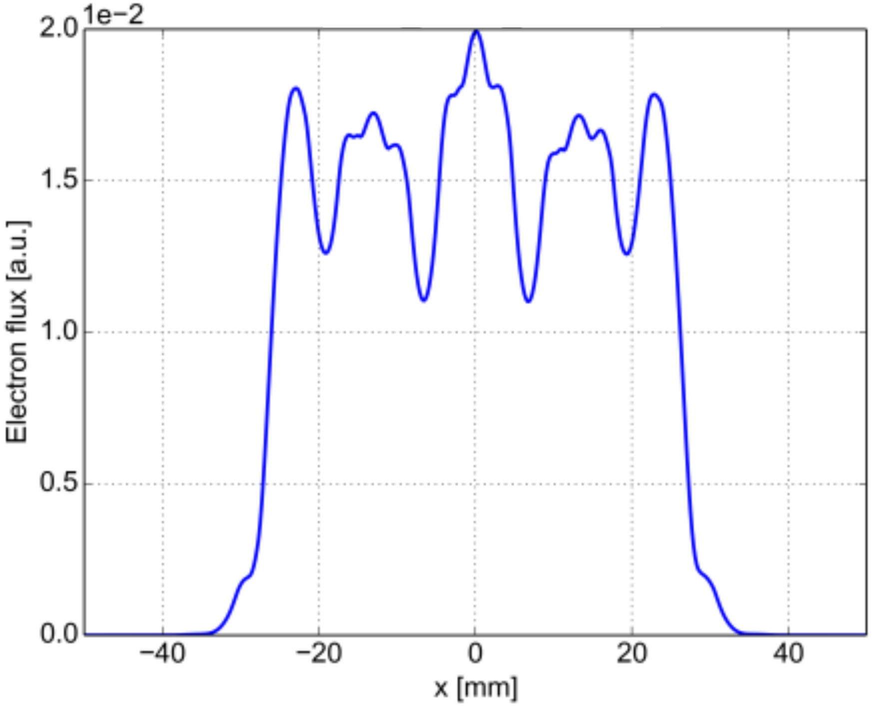
- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
    - Comparing experimental data against simulations for different magnetic fields applied

B = 83 G

Measurement



Simulation

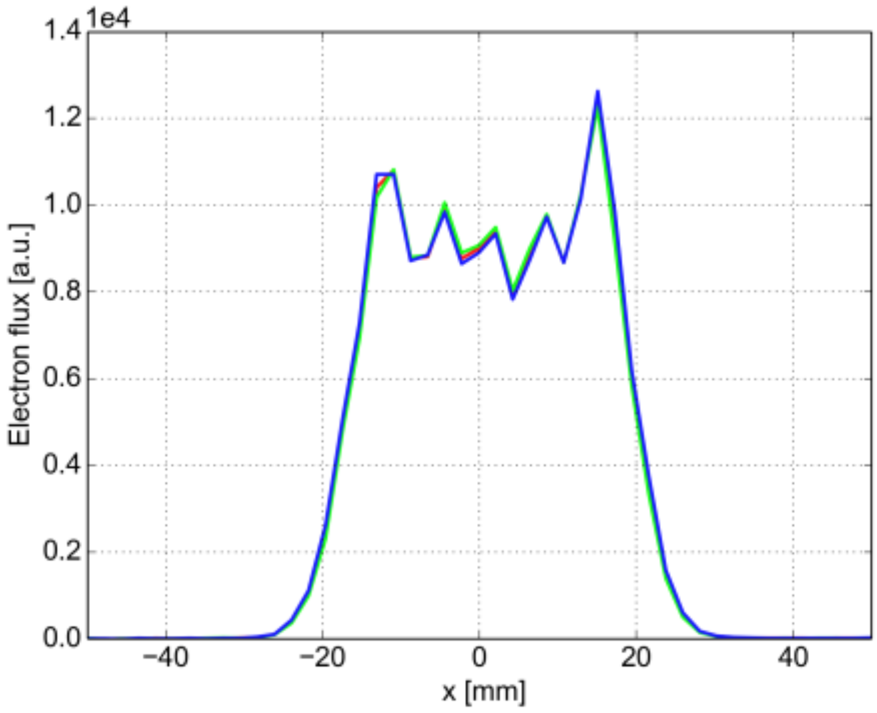


Electron cloud in the SPS

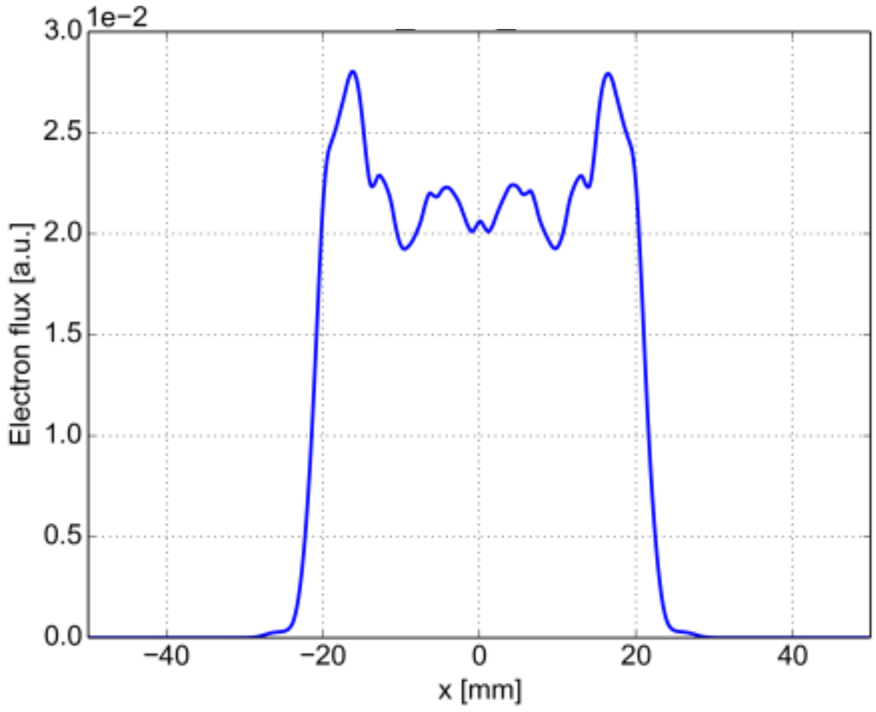
- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
  - Comparing experimental data against simulations for different magnetic fields applied

B = 125 G

Measurement



Simulation

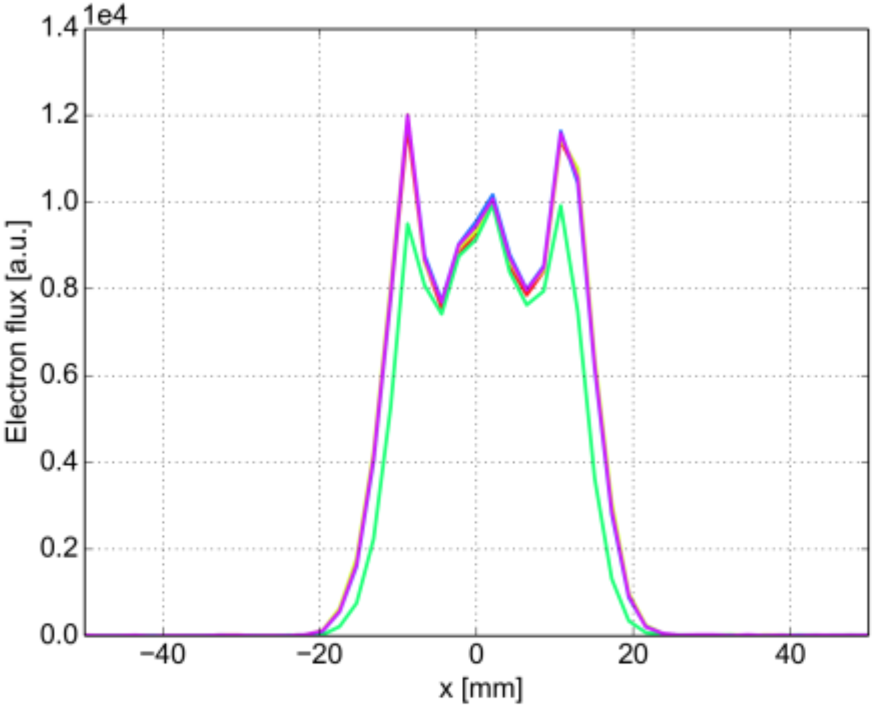


Electron cloud in the SPS

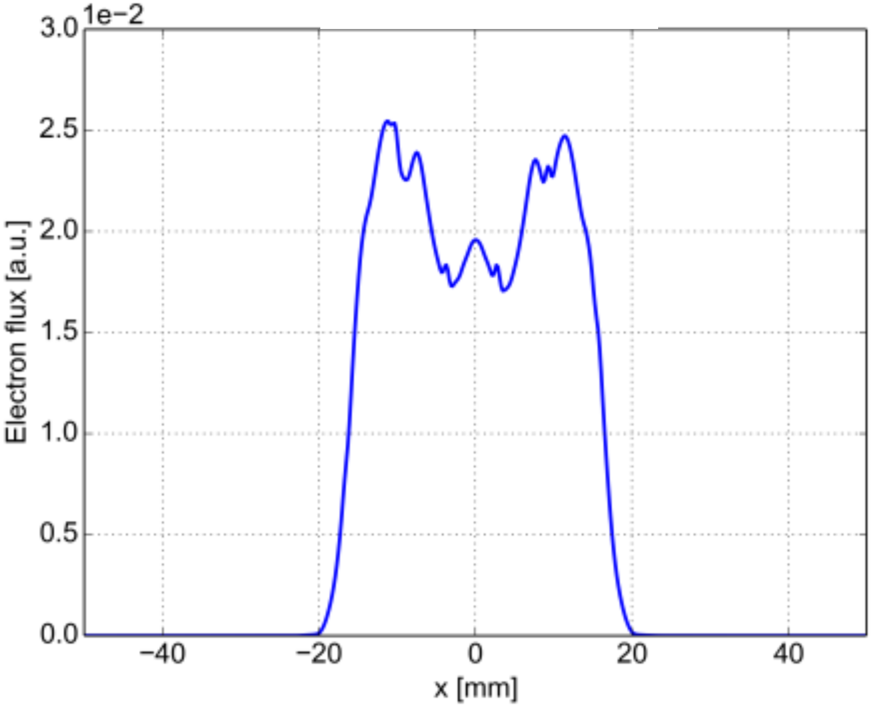
- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
  - Comparing experimental data against simulations for different magnetic fields applied

B = 175G

Measurement



Simulation

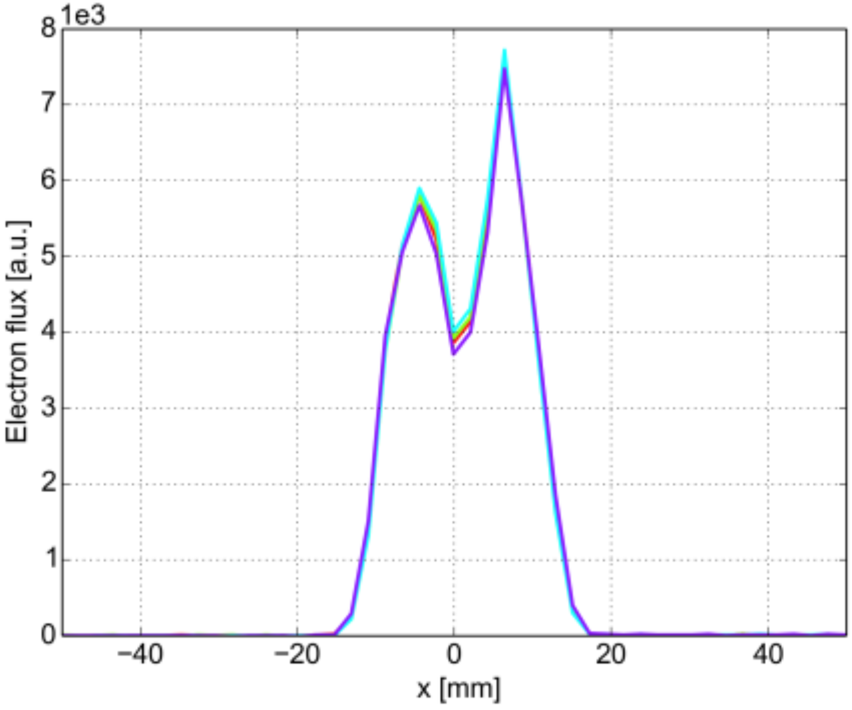


Electron cloud in the SPS

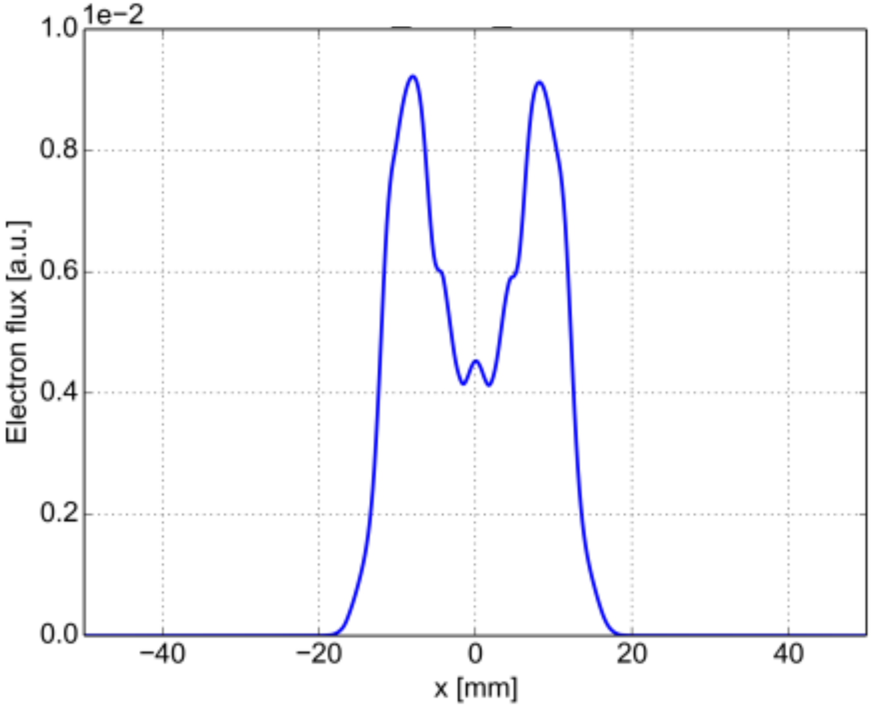
- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
  - Comparing experimental data against simulations for different magnetic fields applied

B = 250 G

Measurement



Simulation



Electron cloud in the SPS

- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
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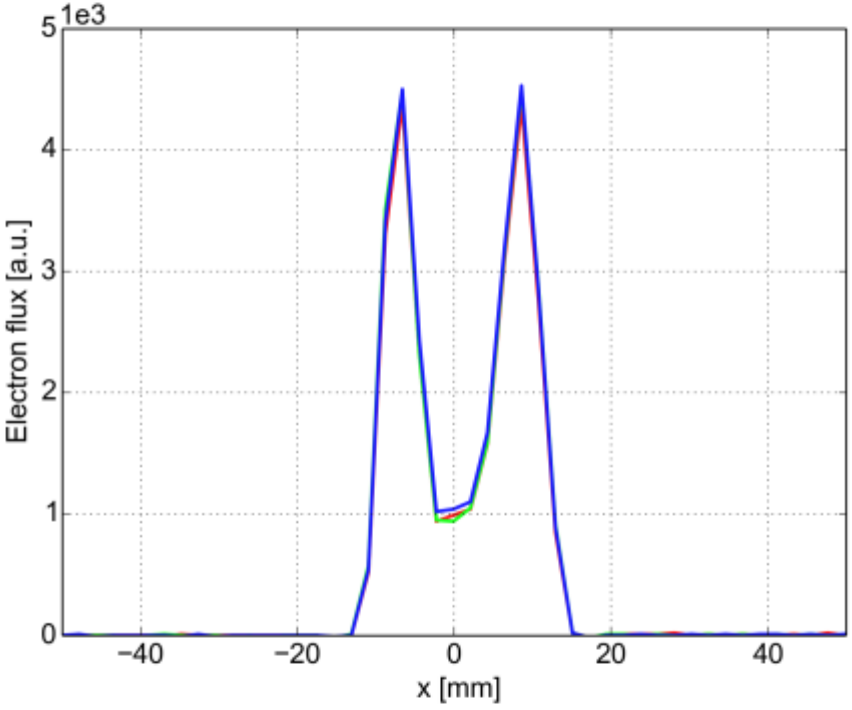
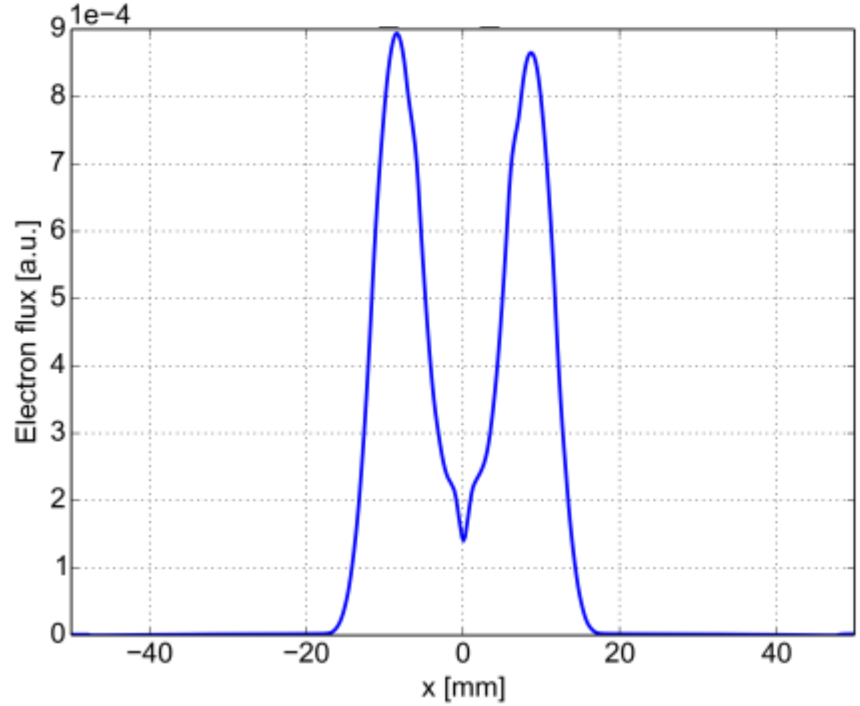
B = 833 G

Measurement



Simulation



Electron cloud in the SPS

- **Strip detectors** installed to measure the integrated signal of electron current through holes in the vacuum chamber
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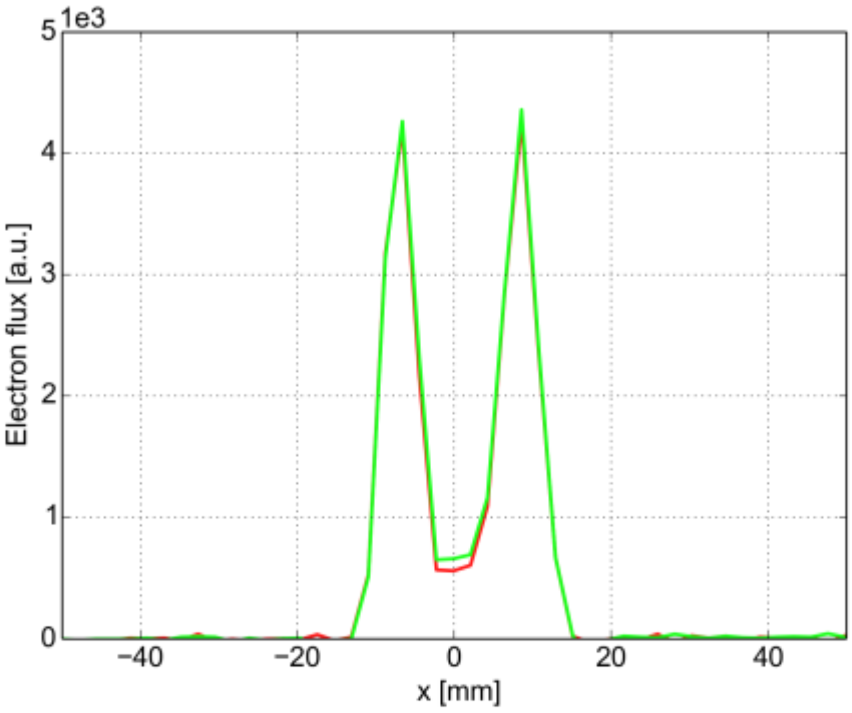
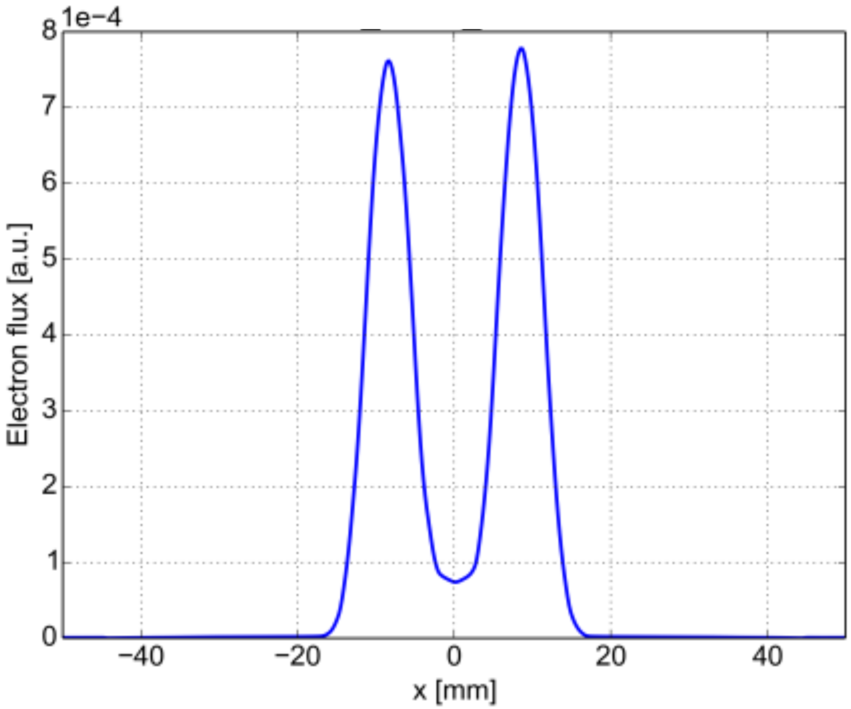
B = 1000 G

Measurement



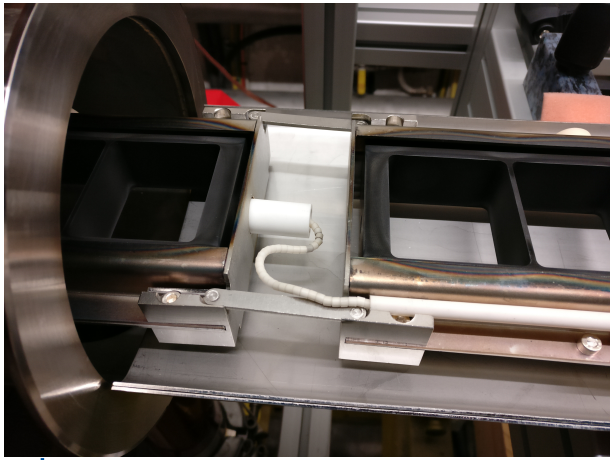
Simulation



Electron cloud in the SPS: the future

- **SPS** is presently producing the beams for LHC within specifications

- In the future, **intensity and brightness out of the SPS will double** and the path against e-cloud is so defined
  - Continue relying on scrubbing on the long term
  - a-C coat selected chambers with low SEY threshold (amounting to about 20% of the total)
  - Continue a-C coating during next Long Shutdown, if necessary



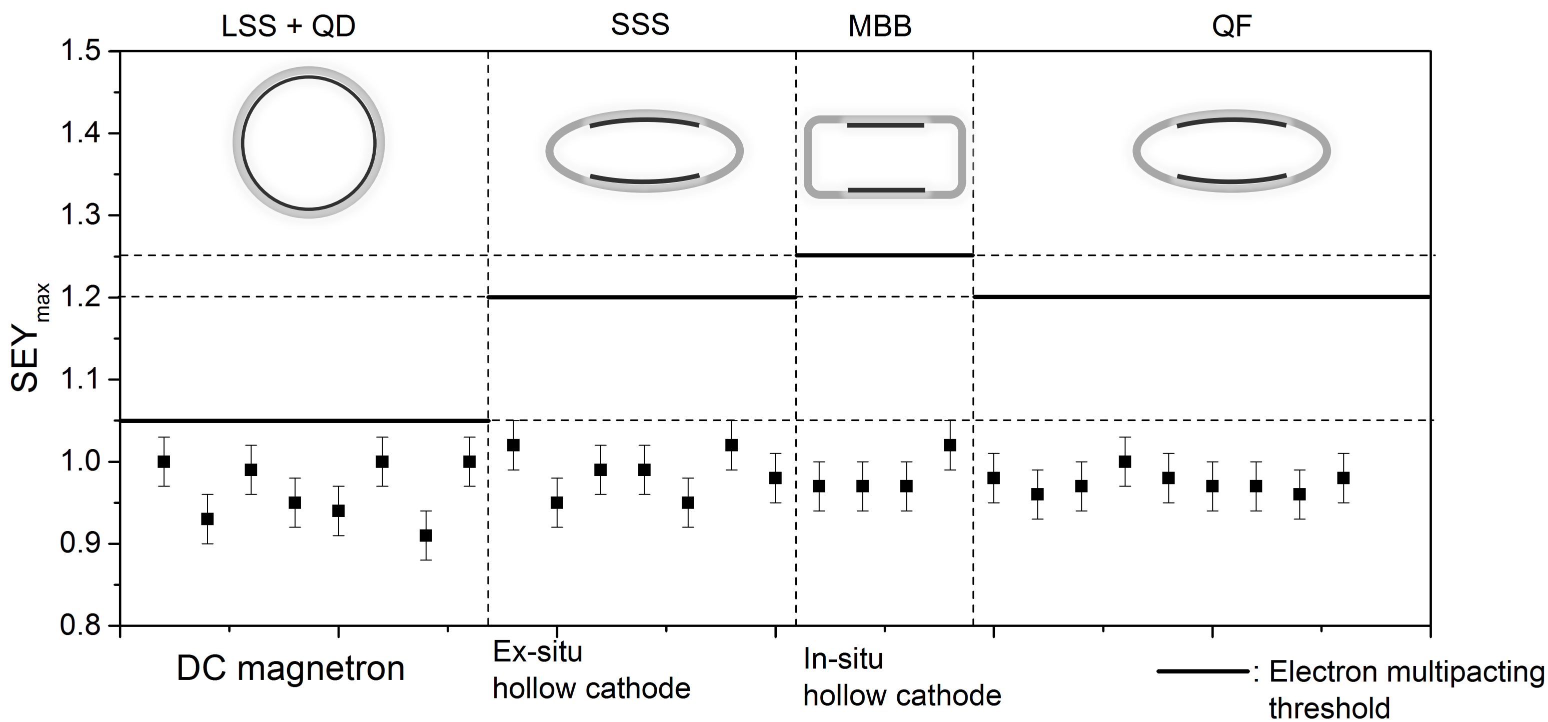
Dipole chamber cathode

Straight Section Chamber cathode

M. Van Gompel & CERN coating team, MOOCA3

Electron cloud in the SPS: the future

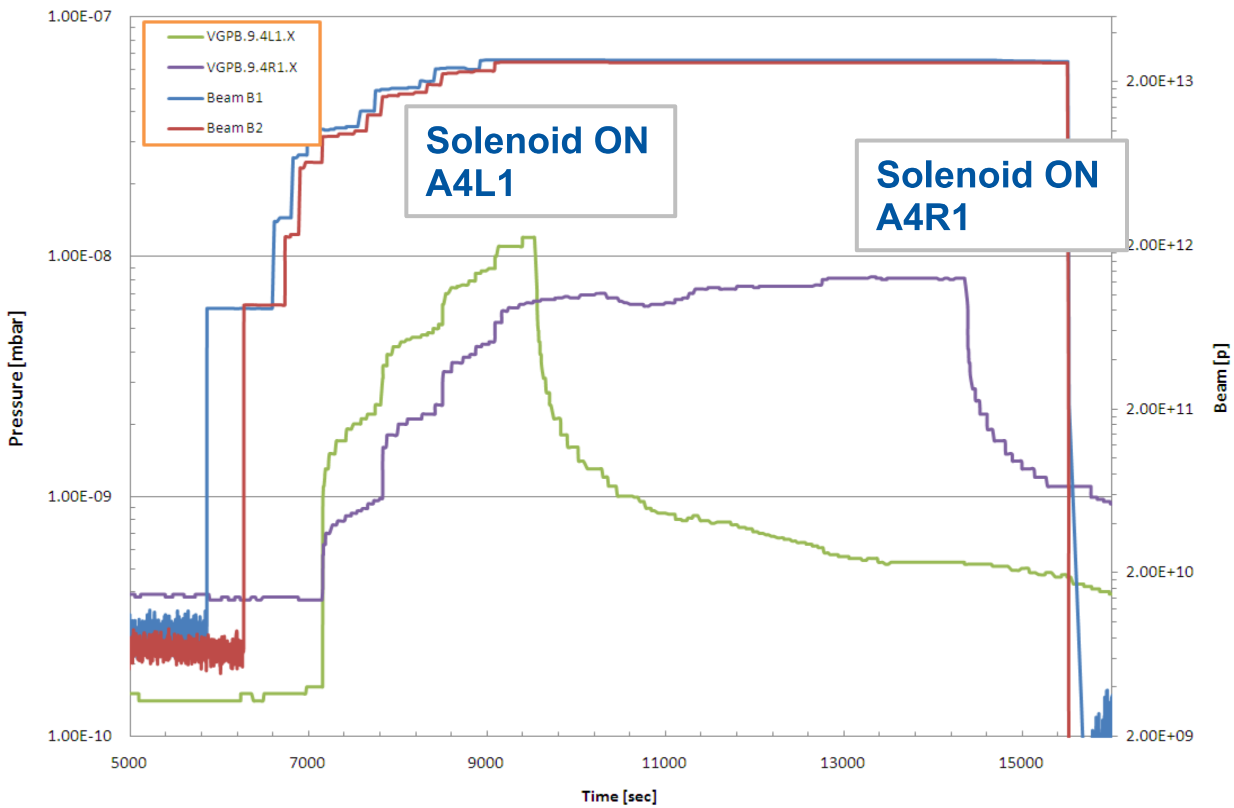
⇒ Logistics for **a-C coating** of different types of chambers successfully proven during the last Technical Stop



M. Van Gompel & CERN coating team, MOOCA3

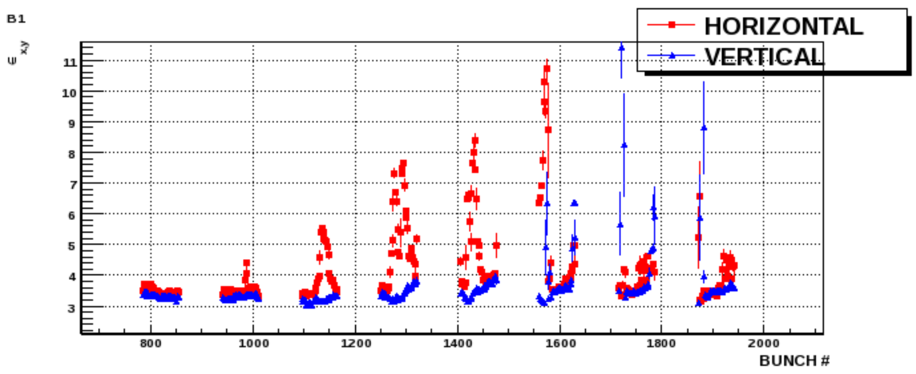
Electron cloud in the LHC

- **LHC** showed first signs of e-cloud with 150 ns beams (2010), but only in the form of pressure rise in the interaction regions
  - **Solenoids** were applied at some locations and worked effectively to suppress locally the e-cloud

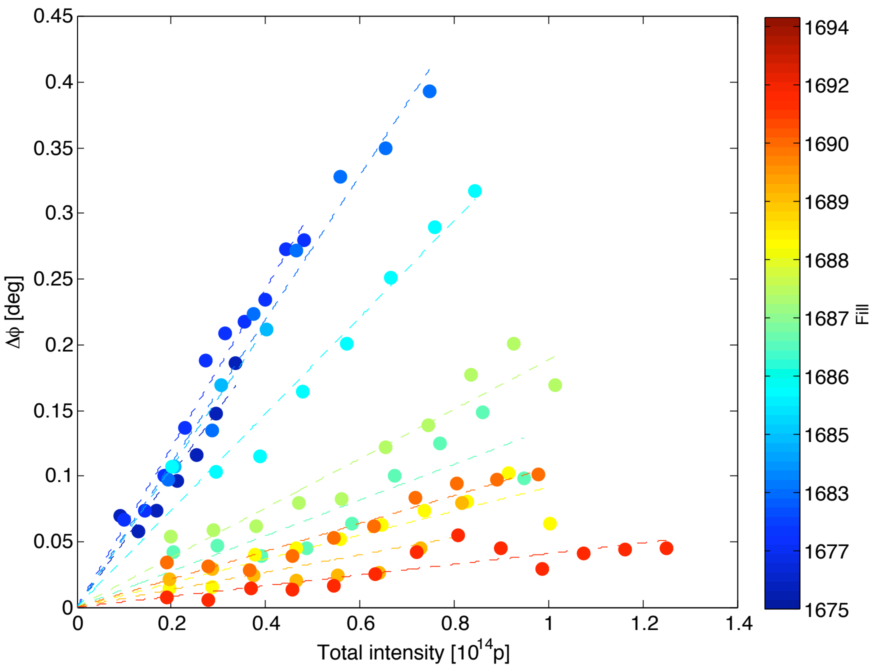


Electron cloud in the LHC

- It was with **50 ns beams** (2011) that clear signs of beam degradation from e-cloud appeared
  - Scrubbing run (10 days) necessary (beginning 2011) to go in physics production with 50 ns beams



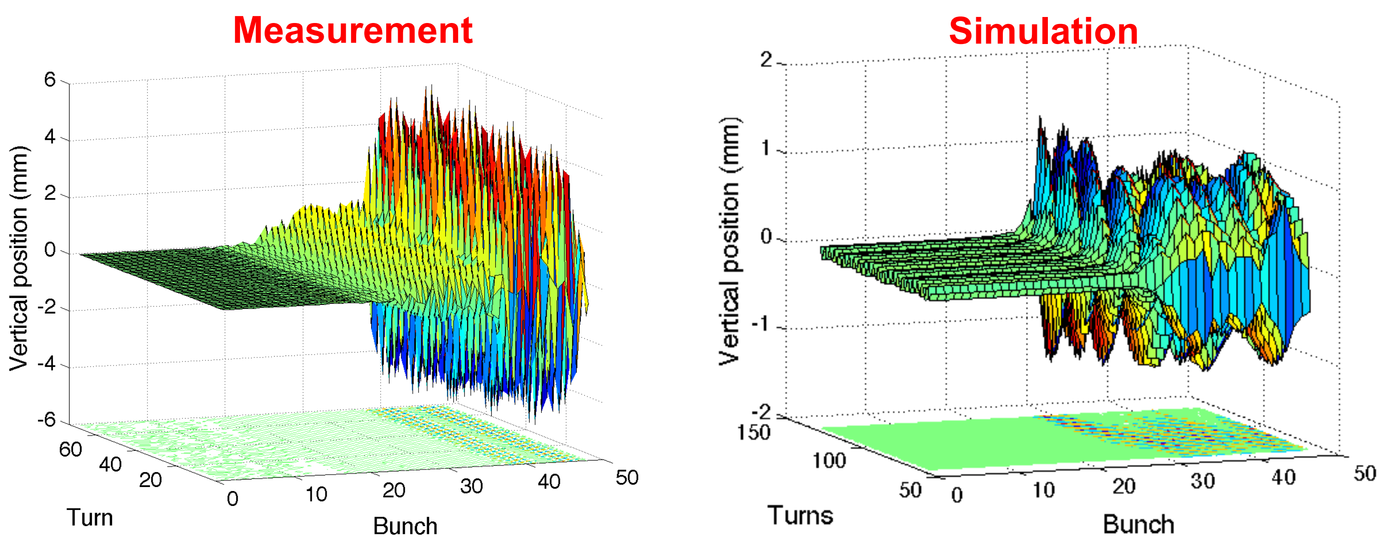
Day 1 of scrubbing – 300 bunches



Electron cloud in the LHC

- It was with **50 ns beams** (2011) that clear signs of beam degradation from e-cloud appeared
  - Scrubbing run (10 days) necessary (beginning 2011) to go in physics production with 50 ns beams
  - However, injection of the first 25 beams led to strong e-cloud driven instabilities → High chromaticity needed at injection

First injection of 48 bunches with 25 ns spacing



Electron cloud in the LHC

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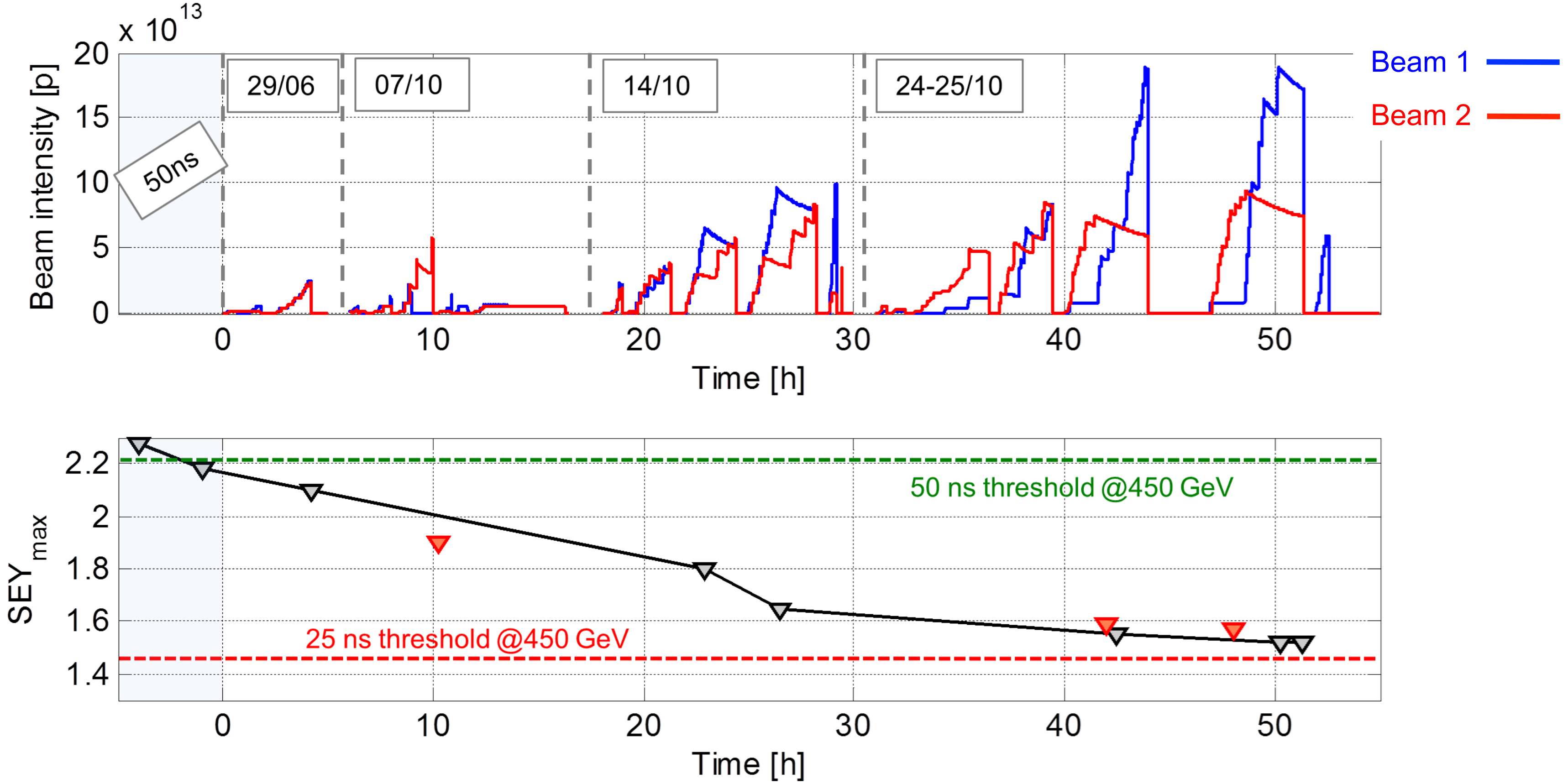
  - Scrubbing run (10 days) necessary (beginning 2011) to go in physics production with 50 ns beams
  - However, injection of the first 25 beams led to strong e-cloud driven instabilities → High chromaticity needed at injection
  - Tests with 25 ns beams in the course of 2011 already provided enough **'conditioning margin'** in the arcs to run stably 50 ns beams for physics throughout 2011 and 2012, without requiring additional dedicated scrubbing runs

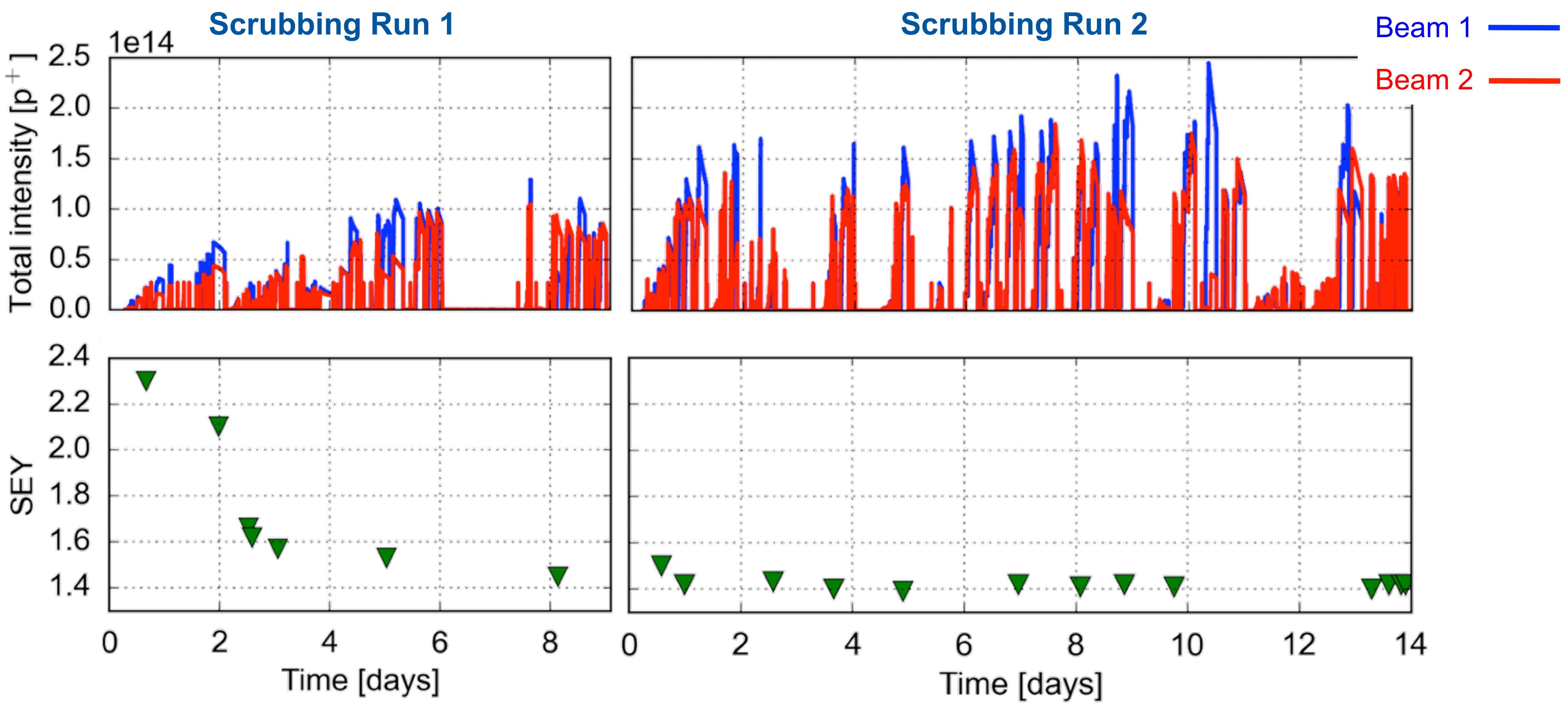
Electron cloud in the LHC

- The evolution of the SEY in the beam screen of the arcs in 2011 could be reconstructed using the **measured heat load data** in combination with **PyECLOUD simulations** done with the measured beam profiles



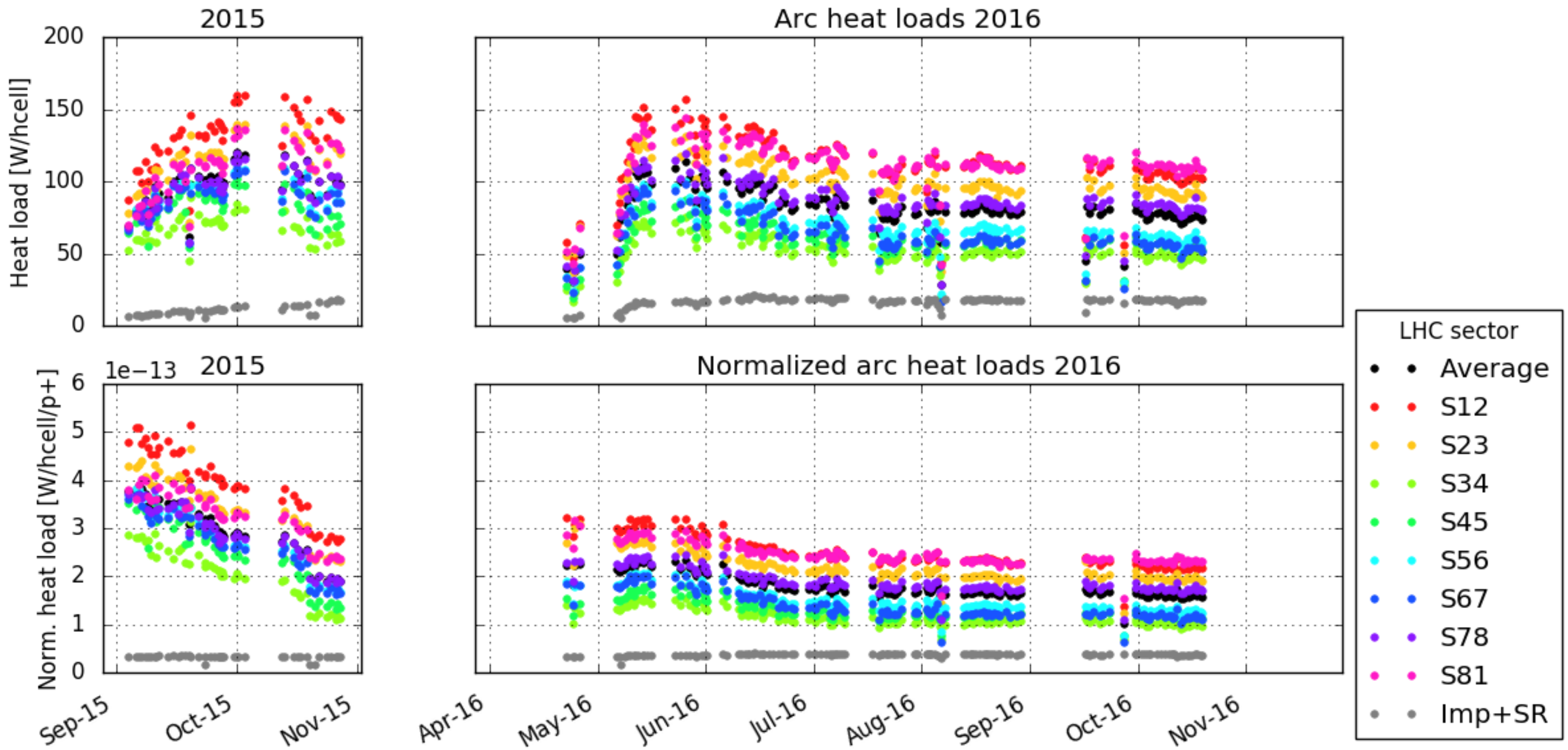
Electron cloud in the LHC

- The scrubbing achieved until end 2012 was undone when LHC was vented during Long Shutdown 1 (LS1)
- In 2015 it took **24 days** of patient and gradual scrubbing to enable LHC to start physics production with 25 ns beams



Electron cloud in the LHC

- To fill LHC with 25 ns beams in presence of electron cloud it has been necessary to run with high chromaticity and octupole currents throughout the cycle (A. Romano's poster, TUPVA018)
- More scrubbing has been accumulated while running for physics with 25 ns beams during 2015 and 2016 (poster TUPVA019)



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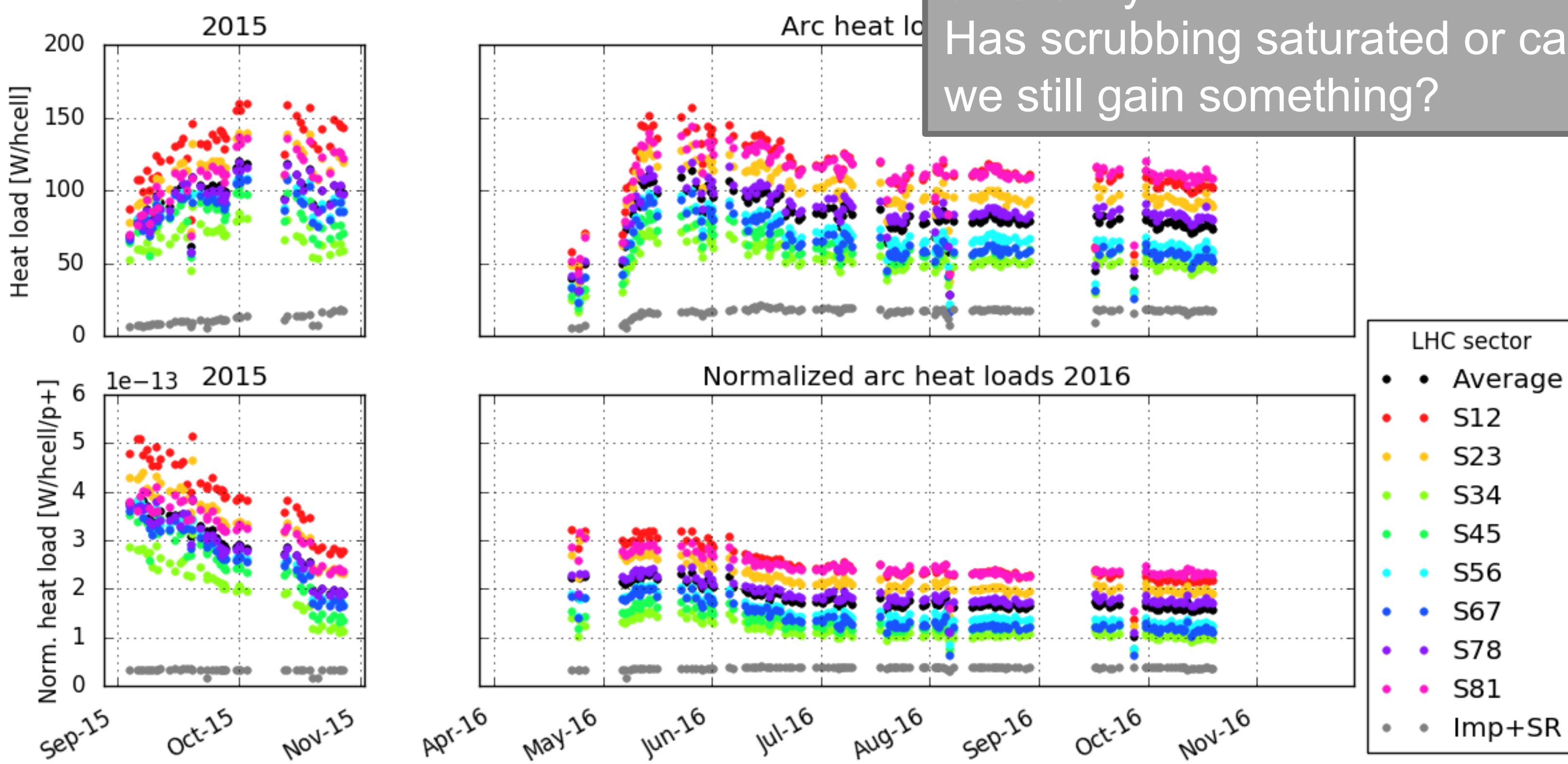
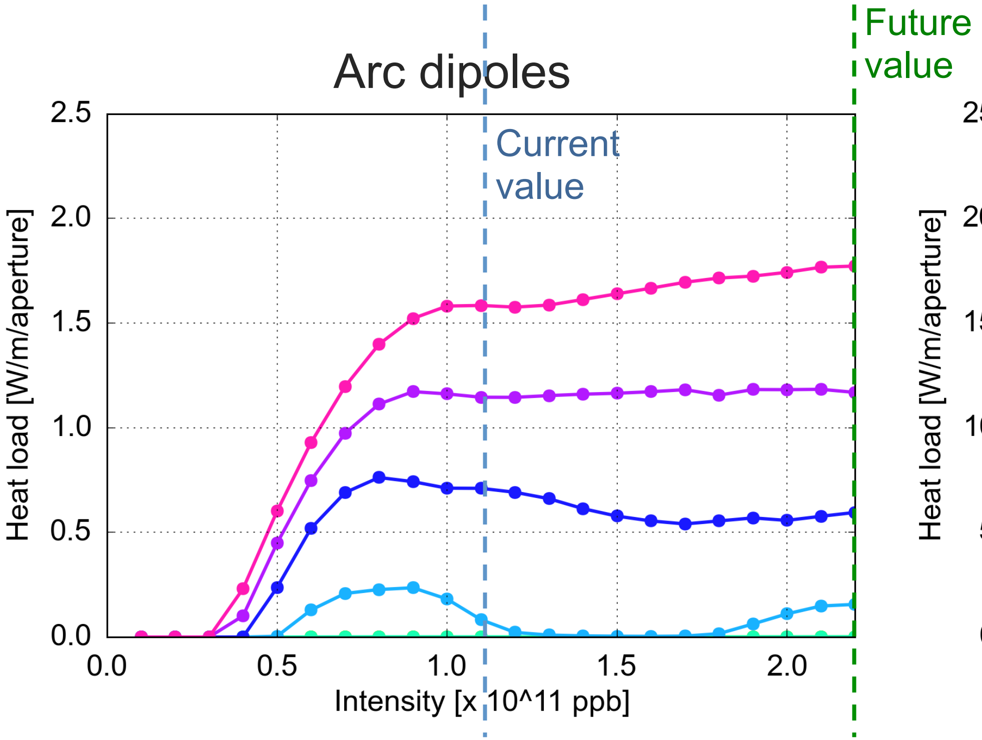
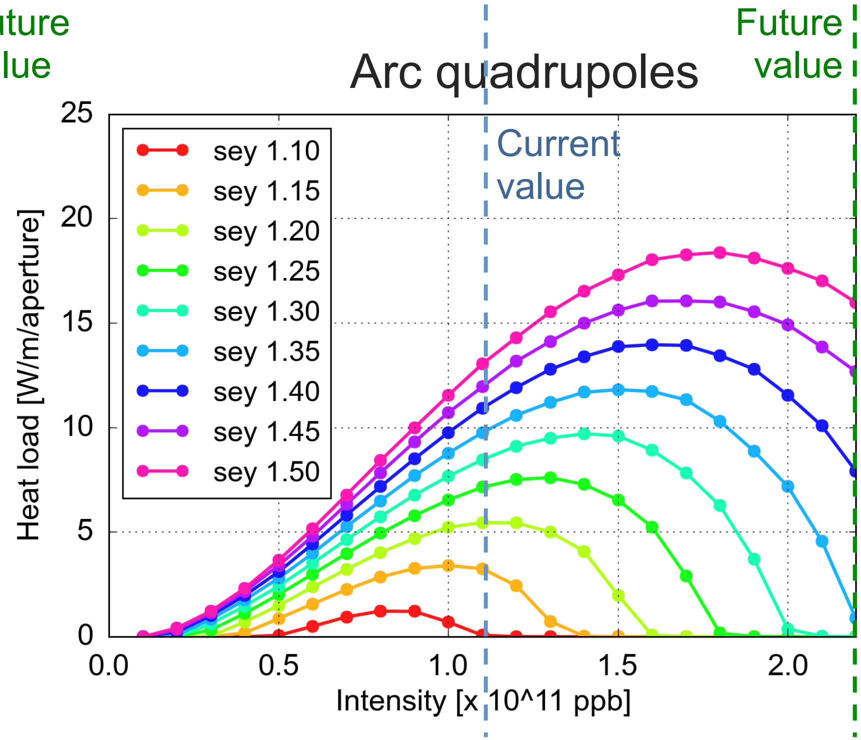
Open questions:
Why do different sectors behave differently?
Has scrubbing saturated or can we still gain something?



Electron cloud in the LHC: the future

- In the **High Luminosity** (HL) era, LHC will also run with **double intensity and brightness**
- Dependence on bunch intensity seems to be favorable in both dipoles and quadrupoles for low enough SEY values (pending experimental verification)



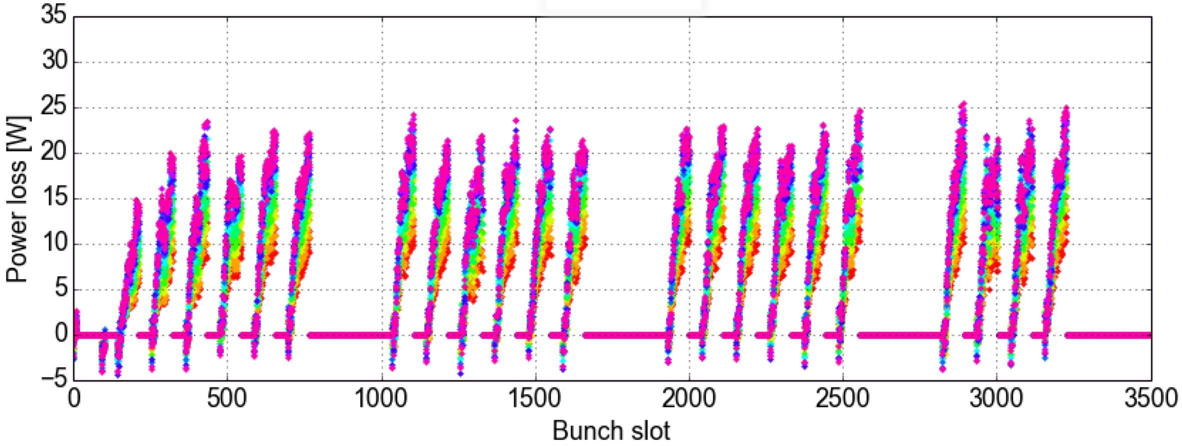


Electron cloud in the LHC: the future

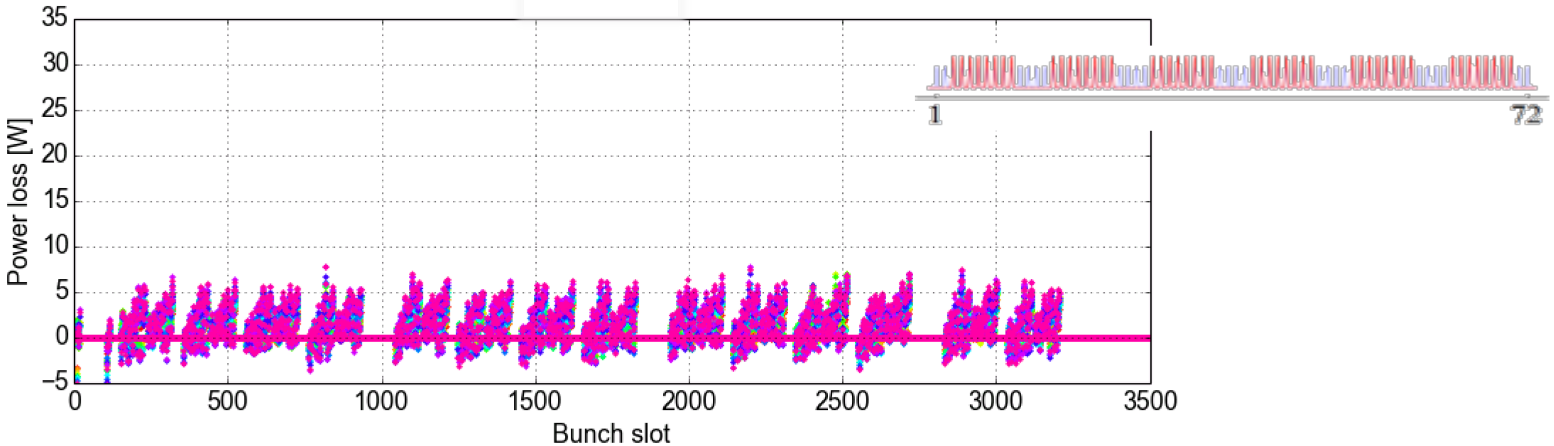
- In the **High Luminosity** (HL) era, LHC will also run with **double intensity and brightness**
- Dependence on bunch intensity seems to be favorable in both dipoles and quadrupoles for low enough SEY values (pending experimental verification)
- **Back up solution**: Use low electron cloud filling patterns with gaps to suppress the build up of the electron cloud (proved to work!)
  - At the expense of the number of bunches in the machine

Electron cloud in the LHC: the future

25 ns beam in full trains of 72 bunches



25 ns beam in trains of 56 bunches with gaps



Closing remarks

- Thanks to intensive measurements and highly empowered simulation tools, we have reached a deep knowledge of the electron cloud in the different CERN accelerators

- Some lessons learnt on the way
  - **Scrubbing** is a formidable weapon to run machines with no surface treatment of the vacuum chamber surface, provided that
    - The SEY threshold for the desired beam parameters is not below the achievable range
    - Efficient ways of **stabilising the beam** (e.g. chromaticity, transverse feedback, Landau damping) can be employed operationally and scrubbing runs are performed
    - Point-like limitations from e-cloud are carefully avoided
  - **Surface treatments** to lower the SEY have been extensively developed and should become baseline for future machines operating with parameters in the e-cloud range (compatibly with impedance and other constraints)

Thank you for your attention